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PURDUE UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

Final Report

FAILURE MECHANISMS IN THIN-FILM RESISTORS

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Abstract

Thin film cermet resistors on glass substrates are tested and analyzed to determine effects of various termination structures and lead connection methods. The effect of a protective coating for the terminations is also studied. Two test groups are used to provide failure data. Test time for the first group is 1500 hours at 125 C; the second group has test times of 480 hours at 150 C. and 670 hours at 175 C.

Termination structures are provided by (1) chrome-copper terminations over cermet resistor film, (2) chrome under cermet plus chrome-copper over cermet, and (3) chrome-gold over cermet. Lead connection methods include (1) welding to termination pads at a position away from the cermet element, (2) welding to termination pads directly above cermet element, (3) localized soldering to termination pad, and (4) soldering to completely-tinned termination pads. Sylgard 182 is used as protective coating for a portion of the termination.

A total of 28 failures are experienced in the group of 144 resistors. These include 17 catastrophic failures in which the resistance changes by 100% or more, 8 drift failures in which the resistance changes by 10-100%, and 3 slow-drift failures with resistance changes of 4-10%. Approximately 25% of the failures (6) are attributed to the fact that soldering leads to the chrome-gold

termination removes significant amounts of gold from the terminations and thus leaves an electrical and mechanical contact of questionable quality.

Data show that the termination process is not particularly important, but that soldered lead terminations are much less prone to failure than welded terminations. Additionally, the coating of Sylgard 182 provides a significant protection for the termination: only one failure (drift-type) is experienced with a coated termination. (The soldered gold types fail for other reasons.)

Analysis of a failed termination by an ARL electron microprobe confirms a high oxygen content on the termination pad and suggests oxidation as the chief cause of failure. Probing the cermet element of resistors which fail indicates that the cermet resistive element is not the cause of failure.

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Panel - refers to a pyrex substrate containing 8 test components deposited as shown in Fig. 1.1.

$R_{14} = R_{T1} = R_1 + R_3 + R_4 + R_2$

$R_{58} = R_{T5} = R_5 + R_7 + R_8 + R_6$

R_{s14} = 100Ω, 1% tolerance resistor placed in series with R_{14}

R_{s58} = 100Ω, 1% tolerance resistor placed in series with R_{58}

R_p = parallel combination of $R_{s14} + R_{14}$ and $R_{s58} + R_{58}$

The above symbols also refer to the voltages across the respective resistor or resistor combinations.

R_c = control resistor. This resistor is used only with the control panels. R_c was chosen such that R_{14} and R_{58} of the control panels were equal.

R_D = voltage dropping resistor. R_D was chosen such that voltage division between R_p and R_D allowed rated power dissipation of all resistors on the panel.

R measured = resistance of test components as determined by recorded voltage readings

$$= \frac{R_i}{R_{si}} \times 10^2 = \frac{V_{ri}}{V_{rsi}} \times 10^2$$

$$= \frac{\text{Voltage across resistance}}{\frac{\text{Voltage across standard } 100\Omega \text{ resistor}}{100\Omega}}$$

R_o = resistance as determined by resistance bridge at ambient conditions prior to initiation of tests

$\Delta R = \dfrac{R \text{ measured}}{R_o}$

$\Delta R_f = \dfrac{R \text{ ambient final}}{R_o}$

NC - non-coated (nc RTV 182 coating on terminations)

C - coated (RTV 182 coating on termination)

C_1 - Connecting leads welded on terminating lands immediately above cermet strip.

C_2 - Connecting leads welded on terminating lands adjacent to cermet strip.

C_3 - Connecting leads attached by soldering to tinned lands.

C_4 - Connecting leads attached by localized soldering.

Subscript - all double numerical subscripts refer to the particular panel. -eg. R_{D43} refers to the dropping resistor used with R_{P43} on panel 10-4-3.

Pad, Termination pad. - the end portions of the resistor to which external leads are connected

S_iO - used as underlayer and protective coating in resistor fabrication.

Cermet - material which constitutes the resistive element of the resistor.

1.0 Introduction

The work described herein was undertaken to establish failure modes in vacuum-deposited thin-film resistors. The resistors used for these tests were fabricated by the Naval Avionics Facility (Indianapolis) and consisted of a total of 5 resistor groups of 4 circuits each, with each circuit utilizing eight resistors, except for 4 "control" circuits utilizing four resistors each. Two panels (Nos. 1 & 2) were prepared by process "A" using pyrex substrate, SiO undercoat, cermet resistor film, SiO protective film and chrome-copper terminations. Fabrication proceeded in the above sequence. Panels 3 and 4 were similarly fabricated except for deposition of a chrome underterminal preceeding deposition of the resistor film; this process was designated "B". A control panel (No. 6) was also prepared by process "A", except for replacing the chrome-copper terminations of process A & B with chrome-gold; this process is referred to as A_1 in this report. Six other variables were introduced by the use of four methods for attaching the gold leads, and by providing a protective coating of Sylgard 182 for some connections while leaving others without a protective coating. The four termination methods are described in the List of Symbols and Definitions. Fig. 1.1 shows a typical resistor structure with its terminal pads.

The life tests were carried out according to the NAFI-designed specifications (See Appendix) such that certain panels were operated in 125° ambient with rated power of 25 watts per square inch, while

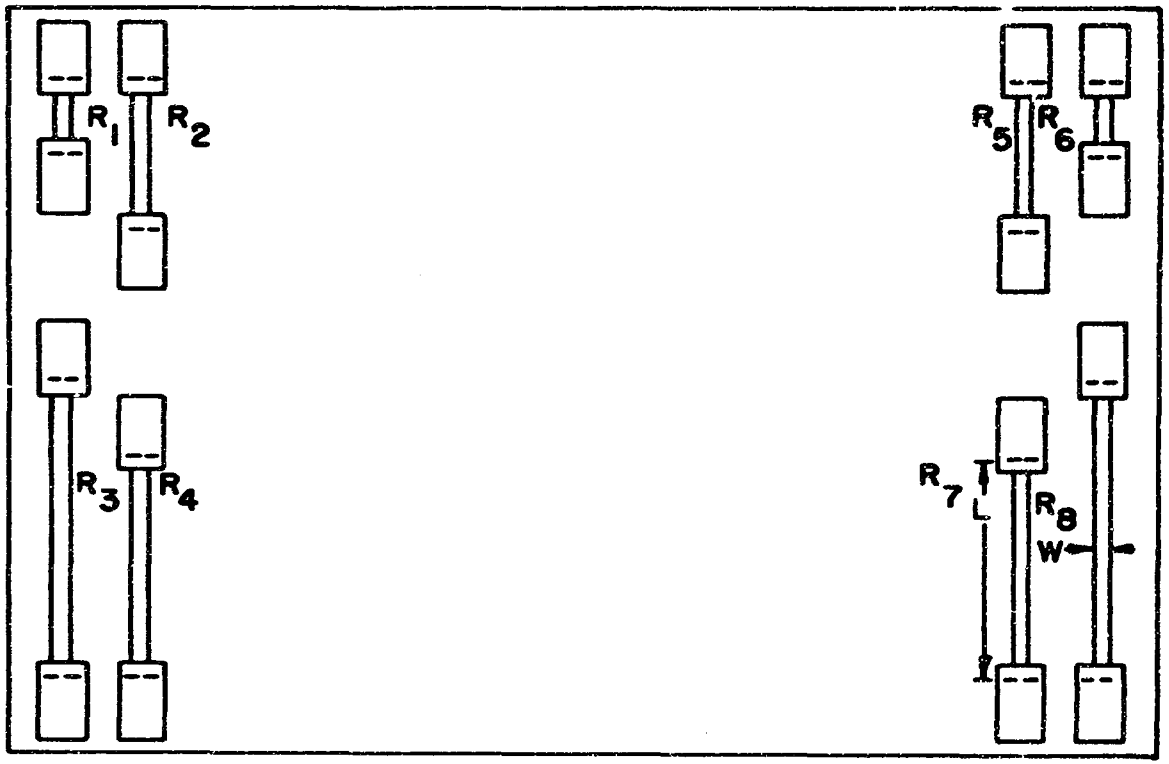


Fig. 1.1 Typical Resistor Pattern

others were operated at 175°C ambient with rated power as above. No attempt was made to control relative himidity though it probably remained under 40% throughout the tests. The electrical test circuits were designed such that resistance readings (as determined from voltage measurements) could be made without removing the resistors from the test ovens. This method assured that failures from high temperature operation were separated from those which might arise from thermal cycling. Chapter 2 covers the test circuits and methods of recording data.

Chapter 3 contains most of the resistance data and gives plots of R/Ro (ΔR) as a function of time. Failures discussed in this chapter are divided into three categories: 1)-Catastrophic, in which resistance values changed from their initial values by more than 100%; 2)-Drift, in which resistance values differ from their initial values by from 10-100%; 3)- Slow Drift, in which changes of 4-10% are experienced. Changes of less than 4% are considered to be non-failure. This chapter also analyzes the data as it is presented, and includes results of electron microprobe analysis showing high levels of oxygen content on the terminal pads of failed resistors. It is also shown that fresh copper pads and fresh bulk copper do not show this high oxygen content. This chapter also includes results of an analysis of catastrophically failed units which have undergone chemical treatment for removal of copper oxide and copper. Probing of the chrome underterminal for representative units gives resistor readings which fall well within the drift or slow-drift categories and indicate no

catastrophic failures of the cermet resistive element. Chapter 4 gives conclusions of this study and recommendations for future work. The Appendix contains schematics, tabulated data and other reference material.

2.0 Methods and Systems for Active Tests

2.1 Experimental Set-up

All resistor panels to be tested at a particular temperature were attached to a single pegboard chassis containing terminal lugs to which the actual resistor wires were attached. Other appropriate wire then led from the chassis, out the door of the environmental oven and through cables and plugs to the test fixture containing the voltage dropping resistors and other connections necessary to assure that each resistor was operating at the proper power level. Terminals were provided on the external test chassis at which voltages could be measured to arrive at the value of either a particular resistor or a group of resistors in series. Figures 2.11 and 2.12 show the terminal arrangements for the low and high temperature tests, respectively. These figures indicate those resistors which were monitored in series with 3 other resistors. In no case were more than 4 resistors in series. Power for the tests was provided by two regulated dc supplies which maintained the set voltage within about 2% regardless of line-voltage variations. Detailed description of all test equipment used for the tests can be found in the Appendix. A brief discussion of the method used to determine the voltages and currents necessary for rated power dissipation is also presented in the Appendix.

2.2 Test Sequence

The high temperature test sequence and the low temperature test sequence differ somewhat. The low temperature test sequence is as

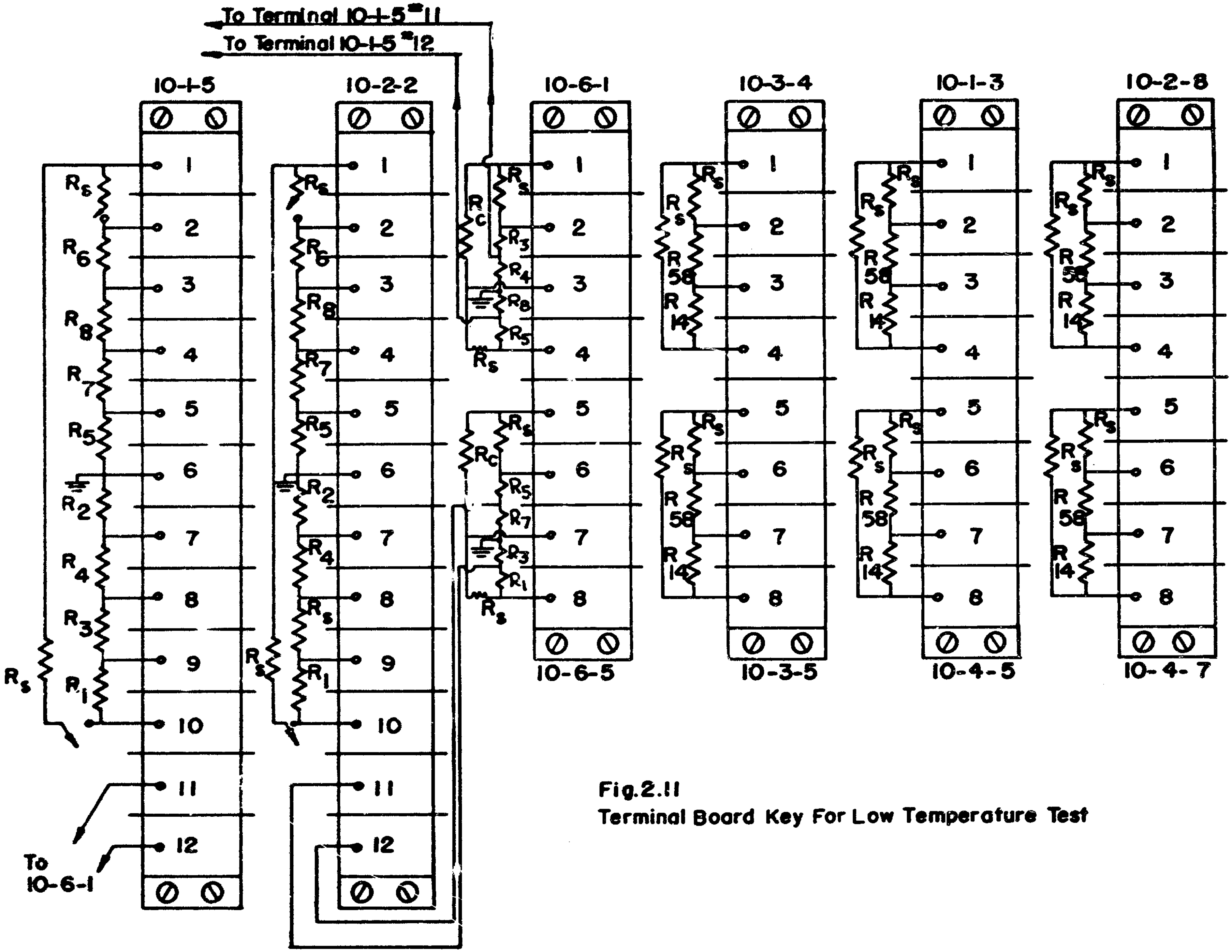


Fig.2.11
Terminal Board Key For Low Temperature Test

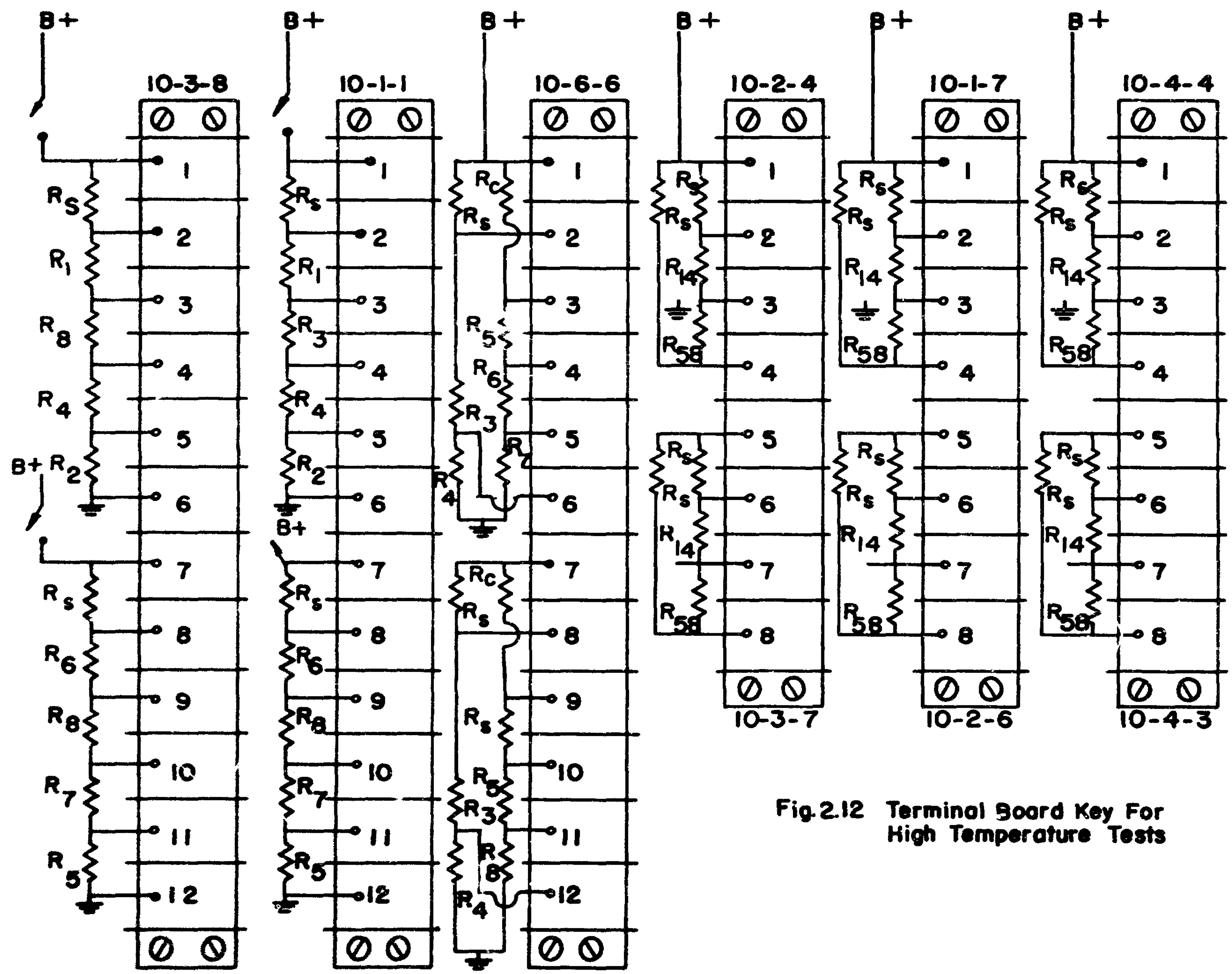


Fig. 2.12 Terminal Board Key For High Temperature Tests

follows:

1) 000 hrs energize circuit and begin readings at 25°C, 25% pwr.
2) 007 hrs Increase pwr to 50%, temperature to 125°C
3) 025 hrs Increase pwr to 100%
4) 400 hrs Increase pwr to 125%
5) 850 hrs Decrease pwr to 100%
6) 850 hrs Discontinue test
   a) Remeasure ambient resistance values
   b) Permanently remove and analyze failures
7) 850 hrs Resume testing of remaining components at 100% pwr and 125°C
8) 1500 hrs Terminate Low temperature test
   a) Remeasure ambient values of all resistors.
   b) Remove and analyze failures.

The sequence followed in the high temperature test is as follows:

1) 000 hrs Energize circuit and begin readings at 50% pwer and 150°C
2) 100 hrs Increase pwr to 100%
3) 480 hrs Increase temperature to 175°C
4) 1150 hrs Terminate high temperature test.
   a) Record ambient values of all test components
   b) Remove and analyze failures

These test sequence differences and total hours test time differences were due primarily to difficulty in obtaining early delivery of teflon-coated wire for use in the high temperature tests.

2.3 Test measurements

Identical measurements were performed in all tests. Each test resistor or series group of resistors was in series with a 100 ohm standard resistor. The voltage across the standard resistor was measured to establish the current in the related resistor group. The voltages across the test resistors or resistor combinations were recorded, and resistance of components was calculated from this data. All voltages were recorded with three significant figures with the third figure being estimated.

The approximate time intervals between readings are as follows:

1. Low temperature test
   a) 000-100 hrs 100% pwr, 125°C 25 hr intervals
   b) 100-400 hrs 100% pwr, 125°C 50 hr intervals
   c) 400-700 hrs 125% pwr, 125°C 50 and 100 hr intervals
   d) 700-1500 hrs 100% pwr, 125°C 50 hrs intervals
2. High Temperature test
   a) 000-500 hrs 100% pwr 150°C 50 hr intervals
   b) 500-1100 hrs 100% pwr 175°C 50 hr intervals

In addition to the foregoing, resistance bridge measurements were taken of the monitor panel resistors, R_1 through R_8 of panel 10-2-2 at 125°C immediately after the 1466, 1500 and 1513 hour voltage readings. Bridge measurements were also taken of R_1 through R_8 on panels 10-1-1 and 10-3-8 at 175°C during the 1095, 1139 and 1153 hour voltage readings. These resistance bridge readings were taken during the final 3 readings of both tests.

3.0 RESULTS AND ANALYSIS

3.1 Available Data

Data available from the total test program can be divided into two categories... one designated as "on-test" and the other "off-test". The on-test data consists of voltage and current measurements related to particular resistors R_1 through R_8 or series resistor combinations designated R_{14} and R_{58} The off-test data consists of:

1. Initial and final resistance bridge measurements of all test components.
2. Measurement of representative component dimensions.
3. Resistance cooling curves of 3 high-temperature test resistors and 2 low-temperature test resistors.
4. Probe resistance measurements using a resistance bridge.
5. Resistance bridge measurements of the monitor-panel resistors at their respective test temperatures.
6. Electron microprobe analysis.
7. All other miscellaneous data.

This data, where appropriate, was plotted, and representative plots are included in this report. In addition to these plots, a brief statistical analysis of the distribution of the values of ΔR was carried out in the high and low temperature tests for measurements involving coated and non-coated terminations.

3.11 Bridge Measurement of Resistance

Tables A_{T3} and A_{T4} give the resistance bridge data for the low and high temperature resistance groups, respectively. This tabulated data was recorded from bridge measurements made before the resistors were placed on test and again after all tests had been completed. The low temperature test resistance data also includes ambient measurements of all components taken at 850 hours. At this time the low temperature test had been interrupted to obtain failure samples for electron micro-probe analysis. These tests were made at room temperature.

3.12 On-Test Data

The on-test data summary sheets are found in the Appendix. Since the actual failures are most important, only those will be listed here. The failures, appropriately grouped, are:

3.121 Catastrophic Failures ($\Delta R > 2.00$)

10-1-5 R_3	Process A	125°C	NC-C_2
10-2-8 R_4	Process A	125°C	NC-C_2
10-2-4 R_3	Process A	175°C	NC-C_2
10-1-1 R_3	Process A	175°C	NC-C_2
10-1-7 R_7	Process A	175°C	NC-C_2
10-6-2 R_4	Process A_1	175°C	C-C_3
10-6-2 R_8	Process A_1	175°C	C-C_3
10-6-2 R_6	Process A_1	175°C	C-C_4

3.122 Drift Failures ($1.10 < \Delta R < 2.00$)

10-1-1 R_6	Process A	175°C	C-C_3
10-6-6 R_3	Process A_1	175°C	C-C_4
10-6-6 R_4	Process A_1	175°C	C-C_3
10-6-6 R_7	Process A_1	175°C	C-C_3

3.12 Slow Drift Failures ($1.04 < \Delta R < 1.10$)

10-1-1 R_2	Process A	175°C	NC-C_4
10-3-8 R_4	Process B	175°C	NC-C_2
10-3-8 R_3	Process B	175°C	NC-C_1

Curves of ΔR versus log (time) for $\Delta R < 1.10$ are shown in Figs. 3.121 through 3.125 as representative plots showing the nature of resistance variation with time. Figures 3.122 and 3.124 are plotted from voltage data for series groups as indicated. The final bridge measurements made it possible to attribute the indicated change to the failure of R_3 (10-2-4) for Fig. 3.122 and the failure of R_7(10-1-7) for Fig. 3.124. Plots of ΔR for ΔR greater than 1.00 for several failures are contained in the Appendix, Fig. A-11.

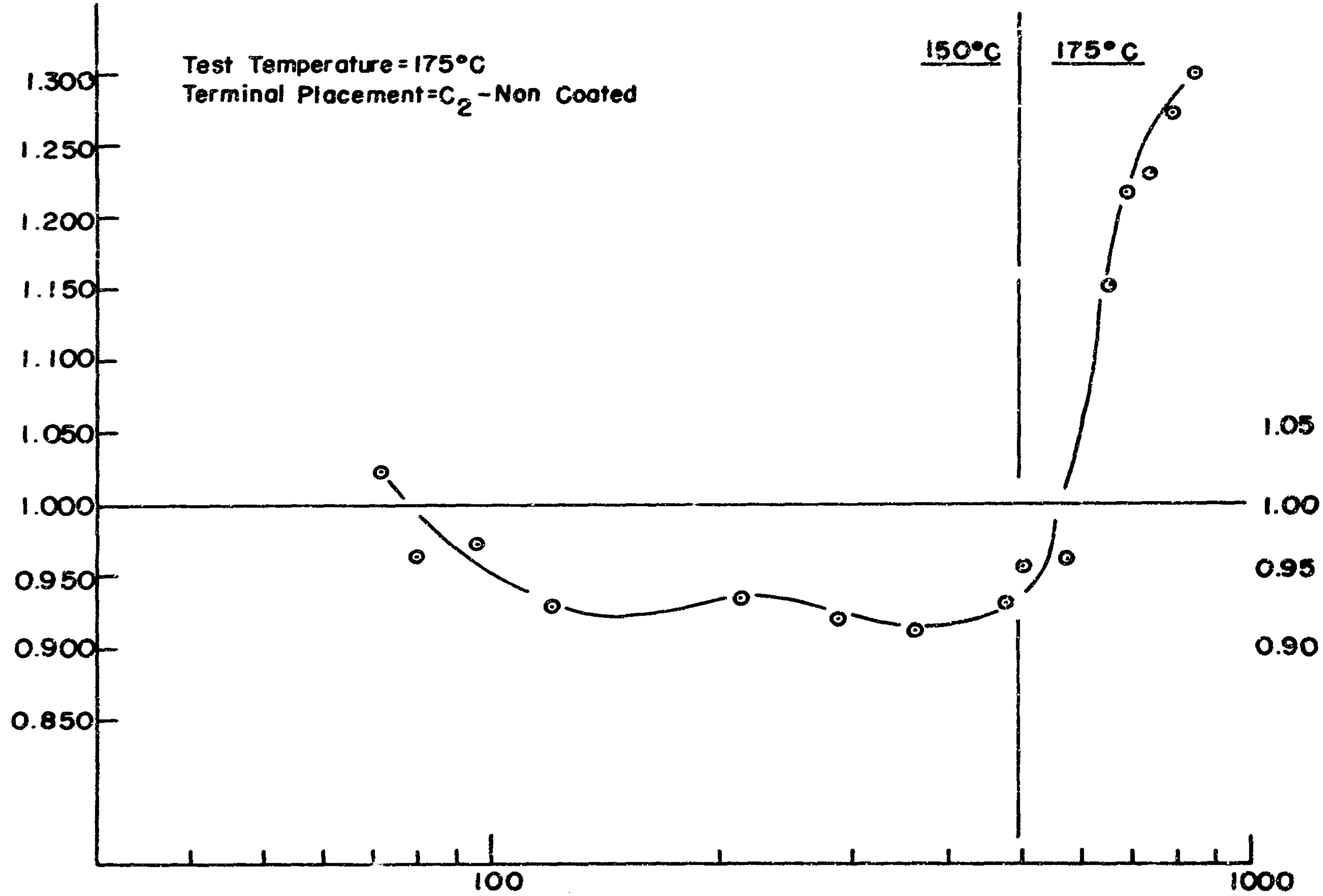


Fig.3.121 ΔR vs Log(Time) For R_7, Panel 10-1-7

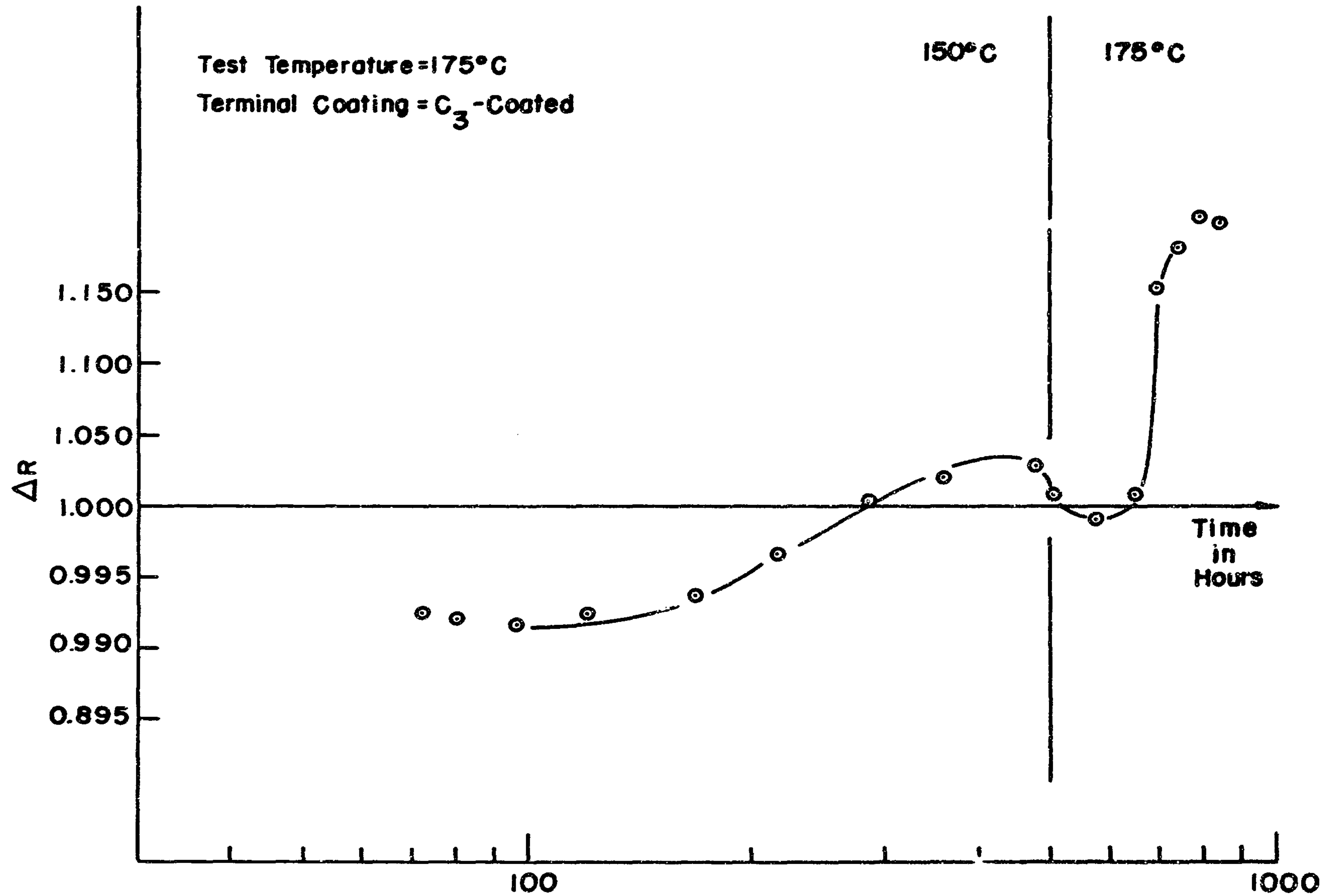


Fig.3.122 ΔR vs Log (Time) For R_6, Panel 10-1-1

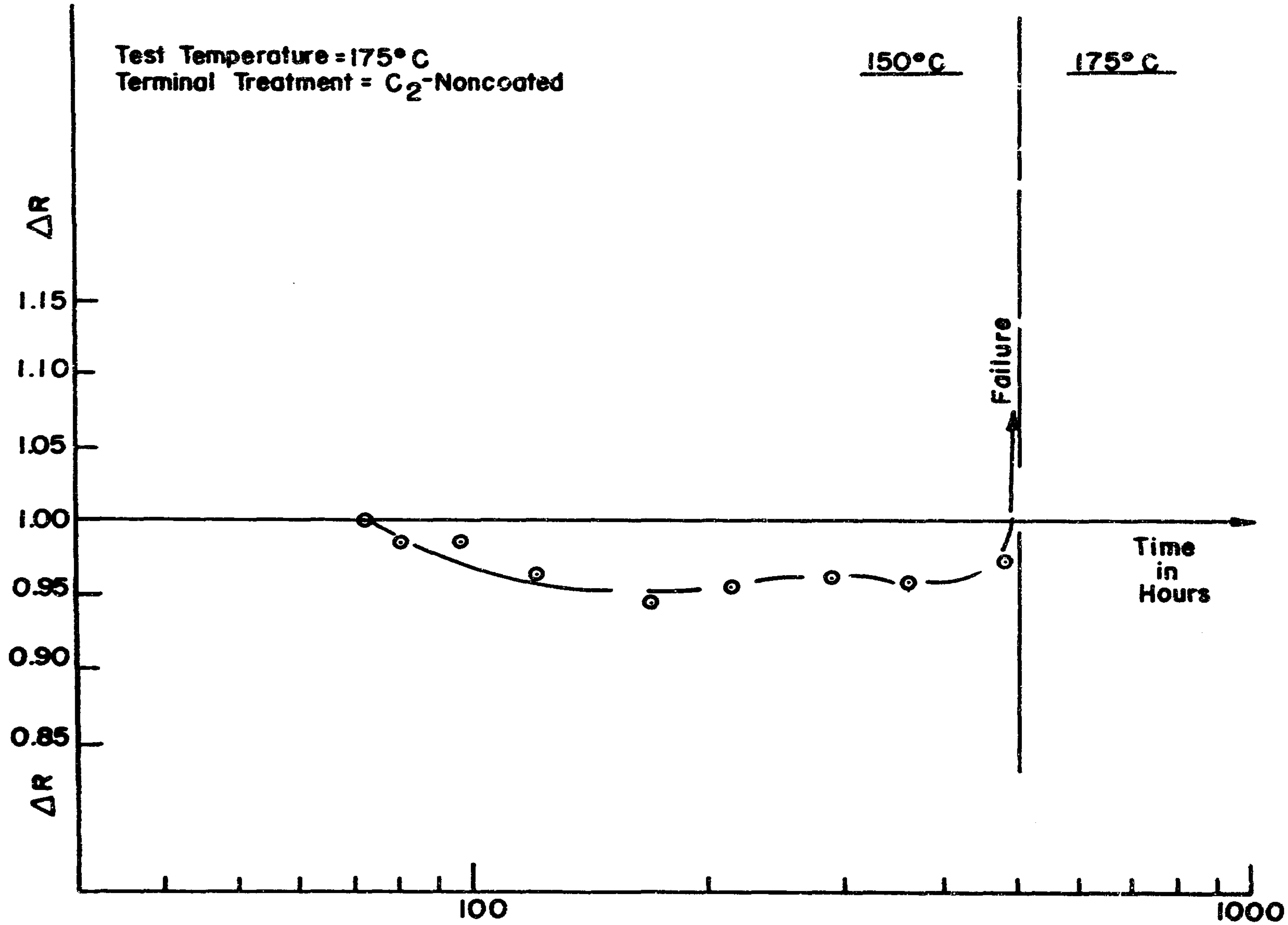


Fig.3.123 ΔR vs Log (Time) For R_3, Panel 10-1-1

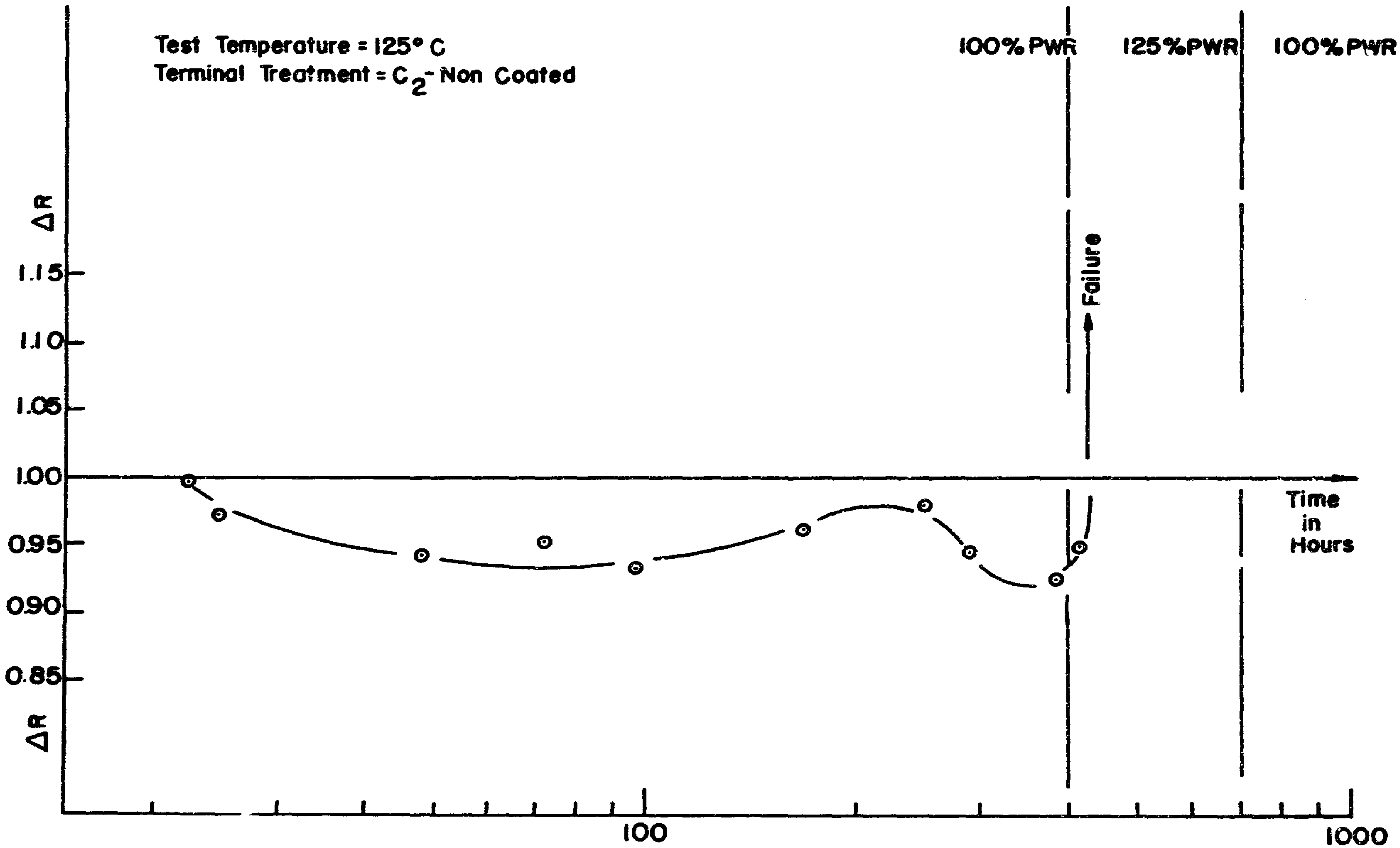


Fig. 3.124 ΔR vs Log(Time) For R_3, Panel 10-1-5

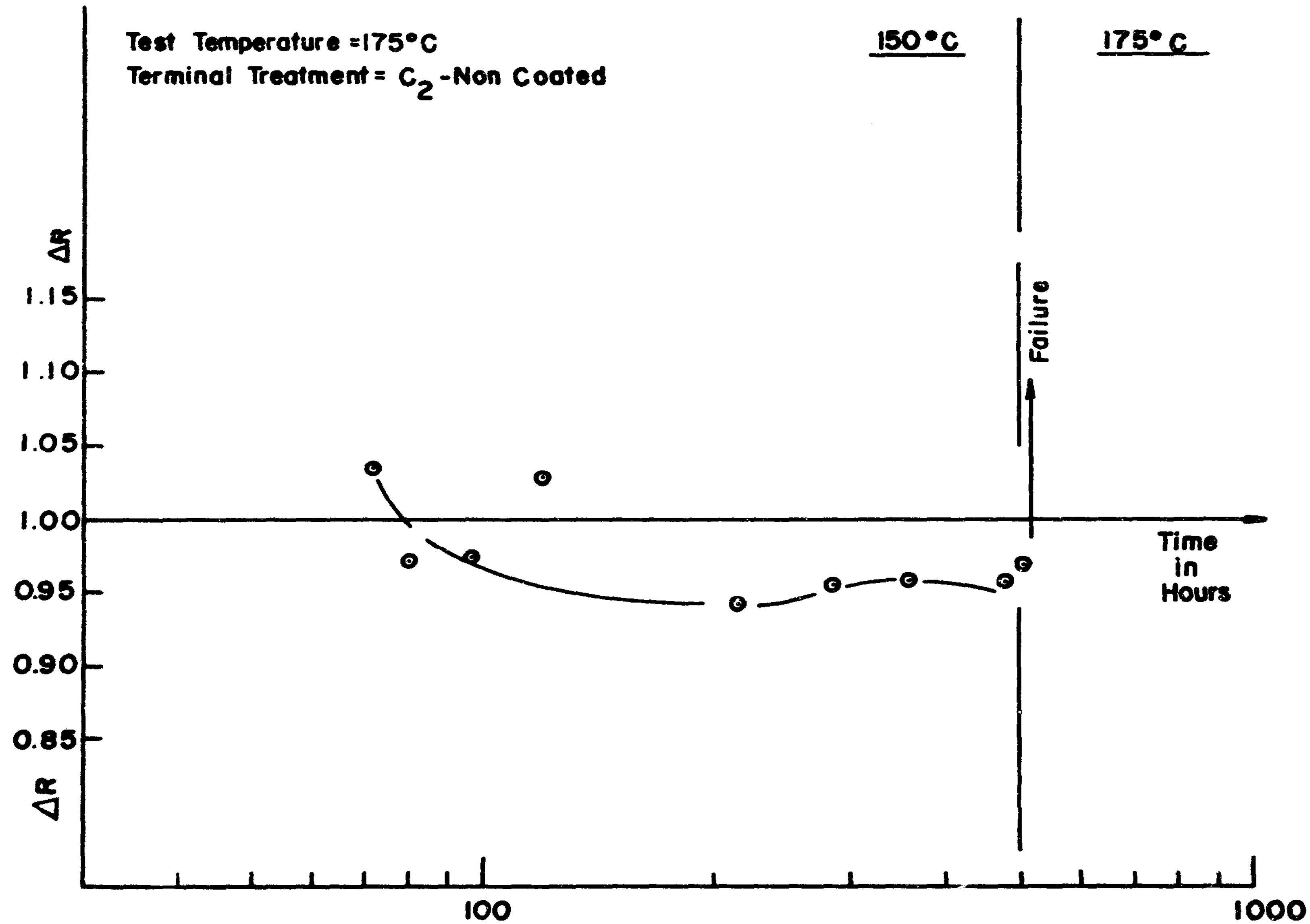


Fig.3.125 ΔR vs Log (Time) For R_3 , Panel 10-2-4

3.13 Off-Test Failure Data

3.131 Failures detected upon cooling.

In addition to the previously listed failures, four drift and nine open terminations (catastrophic failures) were indicated by the final bridge measurements which were not indicated by the on-test voltage measurements. These failures are as follows:

3.1311. Drift failures ($1.10 < \Delta R < 2.00$)

a)	10-4-3 R_1	process B	175°C	NC-C_2
b)	10-4-4 R_6	process B	175°C	NC-C_2
c)	10-2-4 R_2	process A	175°C	NC-C_1
d)	10-2-6 R_6	process A	175°C	NC-C_4

3.1312 Open Terminations

a)	10-4-3 R_4	process B	175°C	NC-C_1
b)	10-4-4 R_7	process B	175°C	NC-C_1
c)	10-2-6 R_7	process A	175°C	NC-C_1
d)	10-3-8 R_3	process B	175°C	NC-C_1
e)	10-3-8 R_4	process B	175°C	NC-C_2
f)	10-1-1 R_3	process A	175°C	NC-C_2
g)	10-2-6 R_5	process A	175°C	NC-C_2
h)	10-3-8 R_1	process B	175°C	NC-C_4
i)	10-3-7 R_7	process B	175°C	NC-C_2

It is felt that these failures were not induced in any way by the final measurement process. When making bridge measurements, the alligator clip leads were attached to the terminal lugs on the pegboard base to

which the gold wires from the resistors were soldered (rather than to the gold wires themselves). This procedure minimized mechanical stresses on the resistor terminations and should have prevented "measurement - caused" failures. The mechanical rigidity of the terminal wires also held the wires in place at the pads and made visual detection of the opened terminations difficult. Microphotographs from sample failures of welded terminations are presented in Plate I.

Plate I

Welded Terminations

(a) Copper oxide appears along the periphery of the weld outline of R_4, panel 10-2-8, which failed catastrophically.

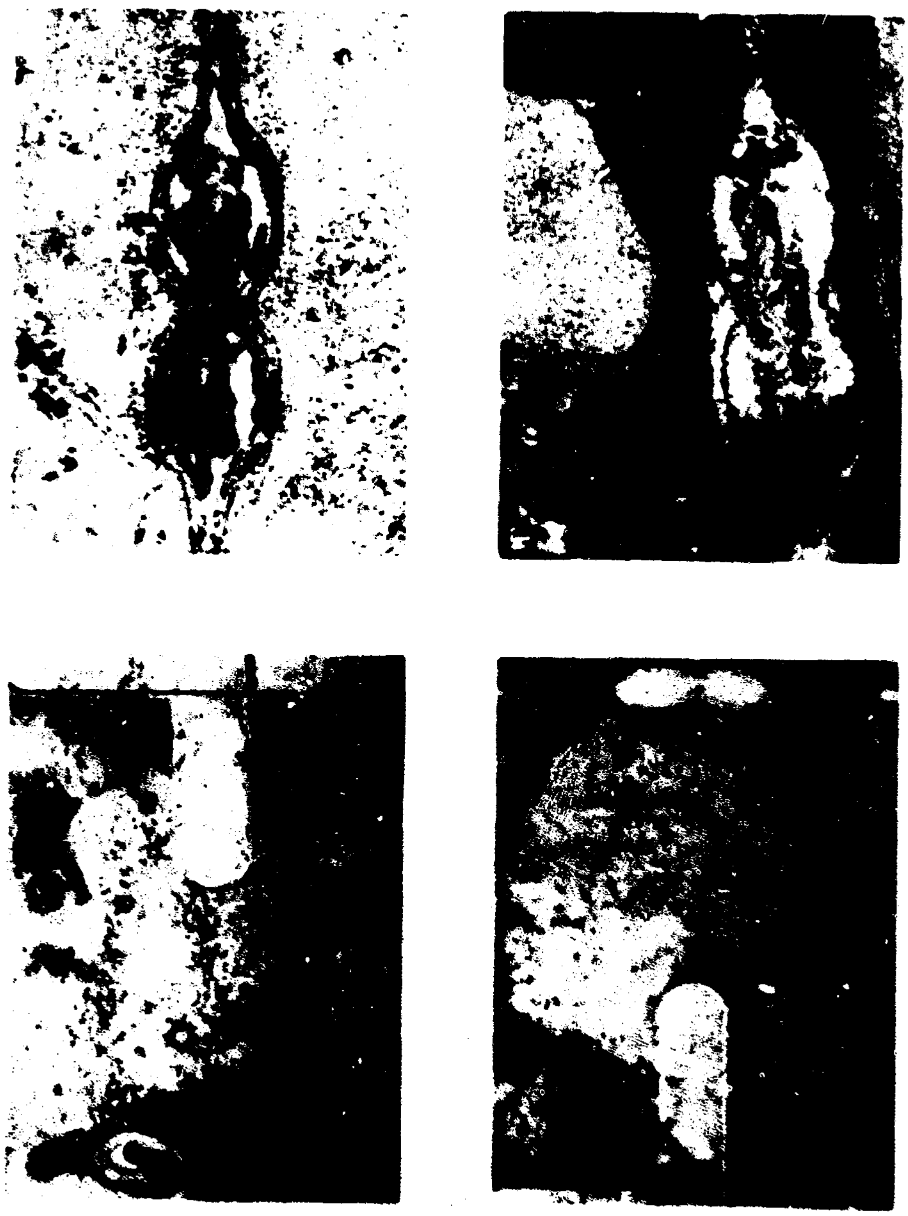
(b) The peeling typical of the high temperature test group, is evident. Weld penetration to the chrome is evident. This photograph is of R_4, panel 10-4-3, which opened during the cooling process.

(c) Large area weld penetration to the SiO underlay is evident.

(d) Weld penetration to, but not through, the chrome is shown.

Plate I

Welded Terminations



3.132-Chemical Etching and Probing

In order to further pinpoint the source of failure, sample panels were etched in nitric acid to remove the copper and copper oxide from the terminal pads. Etching periods ranged up to 45 minutes in duration. Microphotographs were taken of the etched pads as shown in Plate II.

After completion of the etching, the resistors were probed with etched tungsten and with balled gold probes to determine possible changes in the cermet element resistance. Results show that this resistance was relatively unchanged from its pre-test value. Unetched resistors were probed in a similiar manner with similiar results. As an example, R_3, panel 10-2-4, had a 70k ohm resistance as indicated by voltage measurements, a probed resistance of 4.1k ohm, and a pre-test resistance of 3.6k ohm. It should not be inferred here that even this small difference is due to cermet element changes. Rather, the probe measurement is extremely dependent on probe position and it is unlikely that the initial reading could have been duplicated by probing even though the cermet resistance were unchanged.

3.133 Cooling curves.

A cooling curve of resistance versus temperature was conducted on five resistors when the tests were terminated. The results of the cooling curves are as follows:

1.	10-1-1 R_3	Process A 175°C	NC-C_2	$\Delta R \cong .133e^{\frac{337}{T}}$
2.	10-3-8 R_4	Process B 175°C	NC-C_2	$\Delta R \cong .320e^{\frac{202}{T}}$
3.	10-3-8 R_5	Process B 175°C	C-C_3	ΔR max. $\cong$ 1.036
4.	10-2-2 R[illegible]	Process A 125°C	C-C_3	ΔR max. $\cong$ 1.018
5.	10-2-2 R_6	Process A 125°C	NC-C_3	ΔR max. $\cong$ 1.018

Plate II

Chemically Etched Terminations

(a) Terminal pad before etching with HNO_3.

(b) Terminal pad after seven minutes of etching.

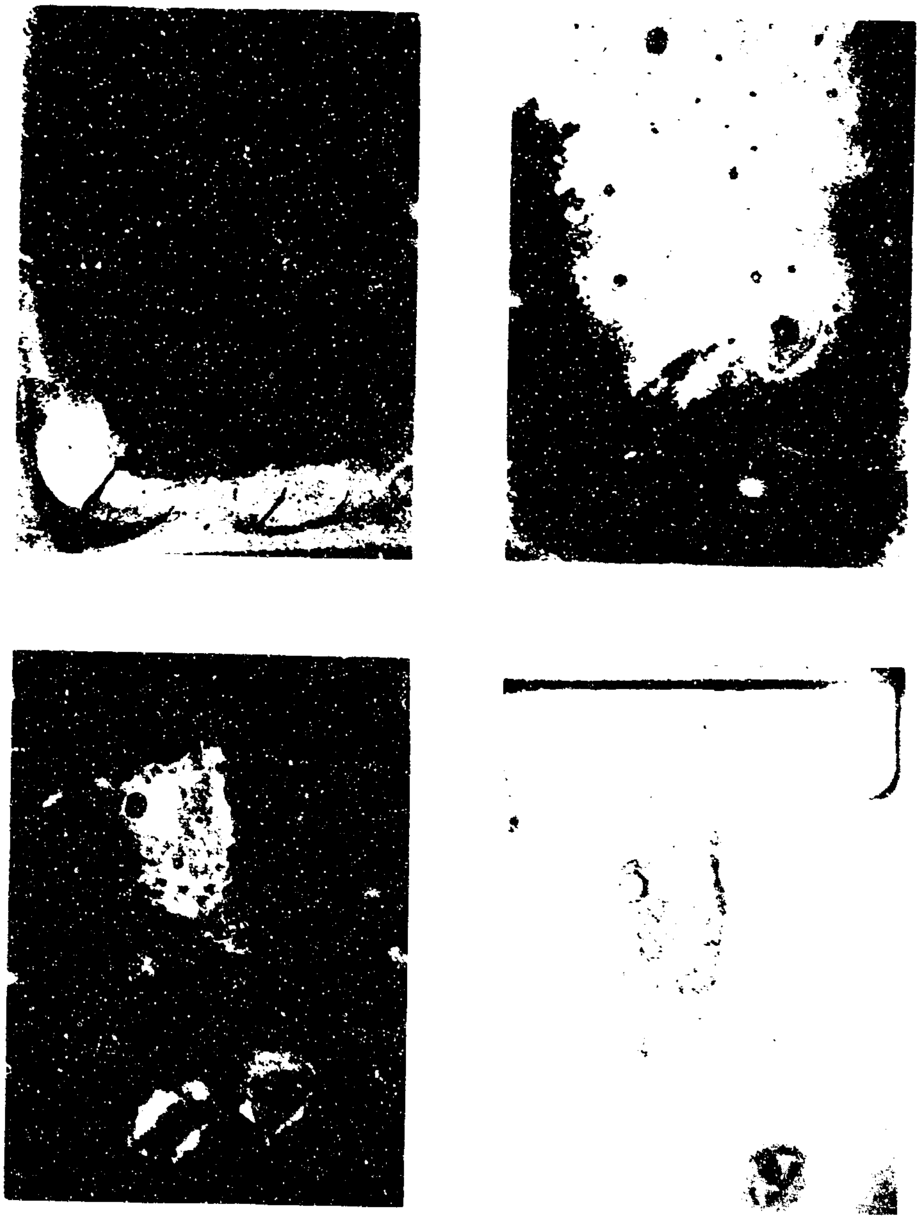
(c) Terminal pad after 15 minutes of etching. (Oblique lighting)

(d) Terminal pad after 15 minutes of etching. (Direct lighting)

Photographs a - d are of the same terminal pad.

Plate II

Etched Terminations



These cooling curves are presented in the Appendix. The cooling curves involving termination type C_3 are approximately parabolic in form. The results of those curves involving welded terminations suggest the possibility that thermal stresses could be partially responsible for failure of the welded terminations. The bridge circuit used to measure the resistances during the two-hour cooling process employed a voltage incapable of exceeding the power rating of those resistors measured. This precaution minimized the possibility of the metering circuits precipitating a failure.

3.134 Electron-Beam Microprobe Analysis

A microprobe analysis was made on the terminal pads of R-3, Panel 10-1-5. This resistor had failed catastrophically in the 125°C full-load test group. The purpose of this test was to confirm the presence of oxygen in what appeared to be heavily-oxidized areas of the terminating pad. No attempt was made to establish absolute concentrations of oxygen. However, comparison of relative oxygen contents of the glass substrate and the oxidized pads was made, as was comparison of oxidized and unoxidized portions of a sample of ordinary copper sheet. Additionally, tests were made on relatively oxide-free, freshly-deposited copper termination.

Resistor 3 of circuit 10-1-5 was chosen for the microprobe analysis because it showed the most radical departure from R_o of the low-temperature groups at the time this test was made. The ARL microprobe was used with beam voltage of 5kv, 80 μ amperes emission current and sample currents in the 10^{-6} to 10^{-8} ampere range.

Figures 3.1341 through 3.1343 give the results of these tests with scales as indicated. Fig. 3.1341 presents data obtained from the most heavily oxidized portion of R-3 adjacent to the point on the pad at which the lead had been attached and from a less heavily oxidized pad on circuit 10-1-5. The oxygen content is indicated by the rather broad peak in the test data plot. Both pads show significant oxygen content, but the less heavily oxidized pad indicates a lesser concentration.

Fig. 3.1342 gives data obtained from a piece of ordinary industrial copper, which had been rather well oxidized and which had been scratched with a fine point to give a "pure" copper surface. Relative differences in oxygen level are evident; however, since this was not a really pure, oxygen-free copper, the presence of some oxygen on the bright copper is not surprising.

Fig. 3.1343 give a plot of microprobe result from the pyrex glass. This does, of course, show oxygen content, but of lesser magnitude than that obtained from the oxidized pads. Since oxygen content indications in the freshly-deposited pads were an order of magnitude less than data presented in Figs. 3.1341 through 3.1343, these data are not shown. By comparison to the other plots, the fresh copper pads were virtually oxygen-free.

3.2 Miscellaneous Results

3.21 Microphotographs

Microphotographs are presented in Plates III, IV, and V in the Appendix. Plate III provides comparison of the surface conditions of terminal pads which are typical of their respective test group. Plate

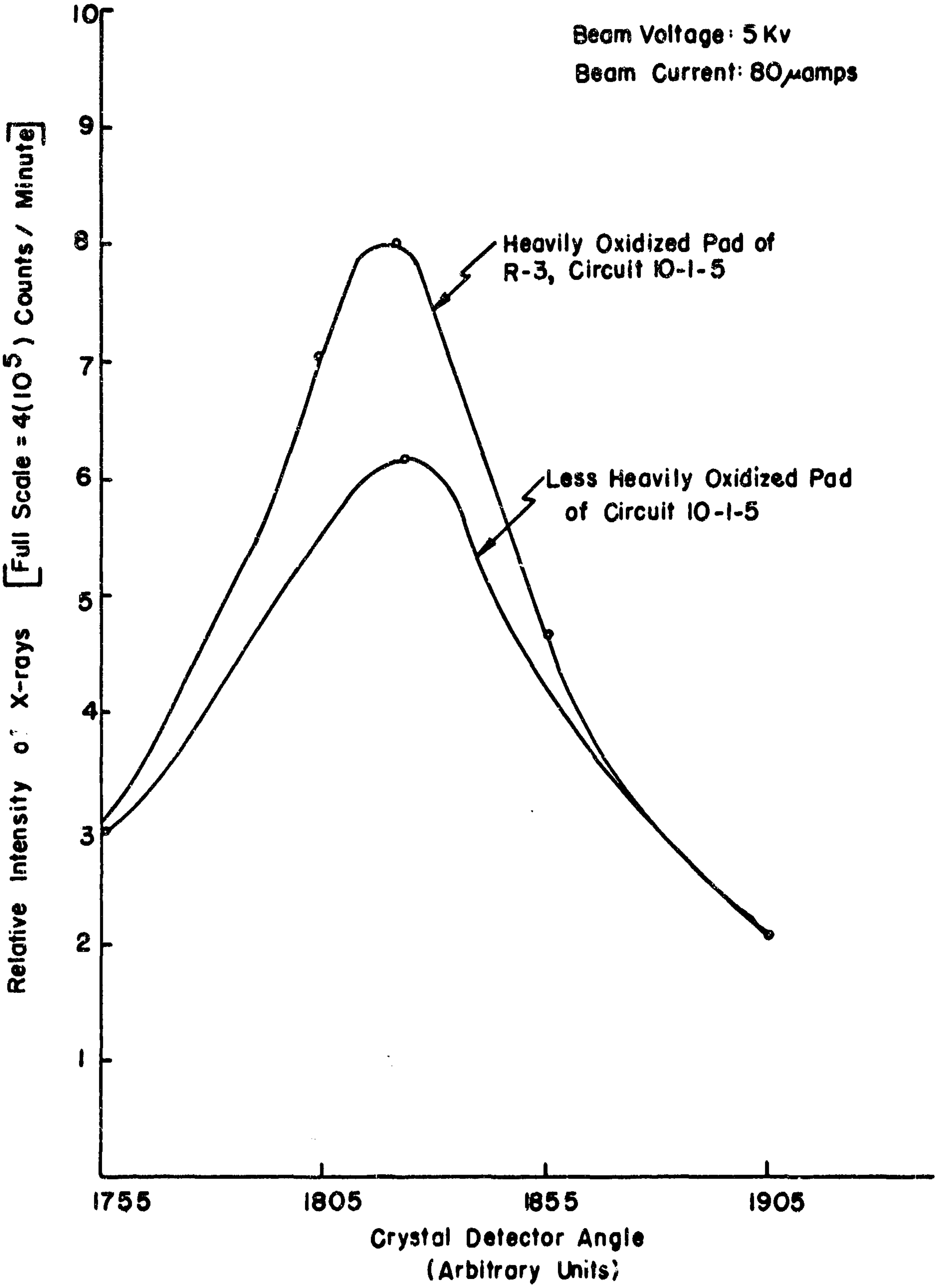


Fig. 3.1431 Microprobe Response From Oxygen Content of Two Oxidized Terminals of Circuit 10-1-5

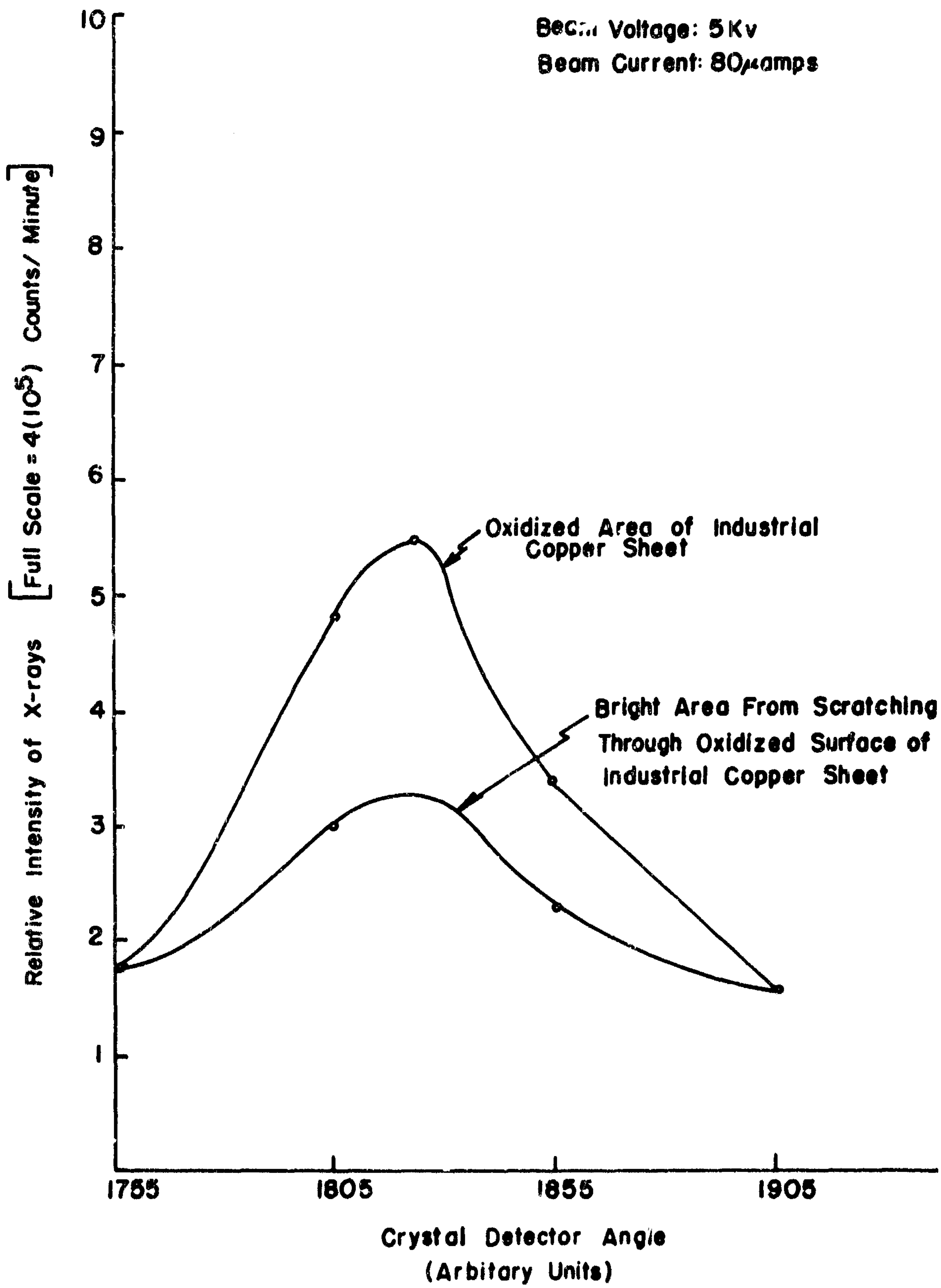


Fig. 3.1432 Microprobe Response From Oxygen Content of Industrial Grade Copper Sheet

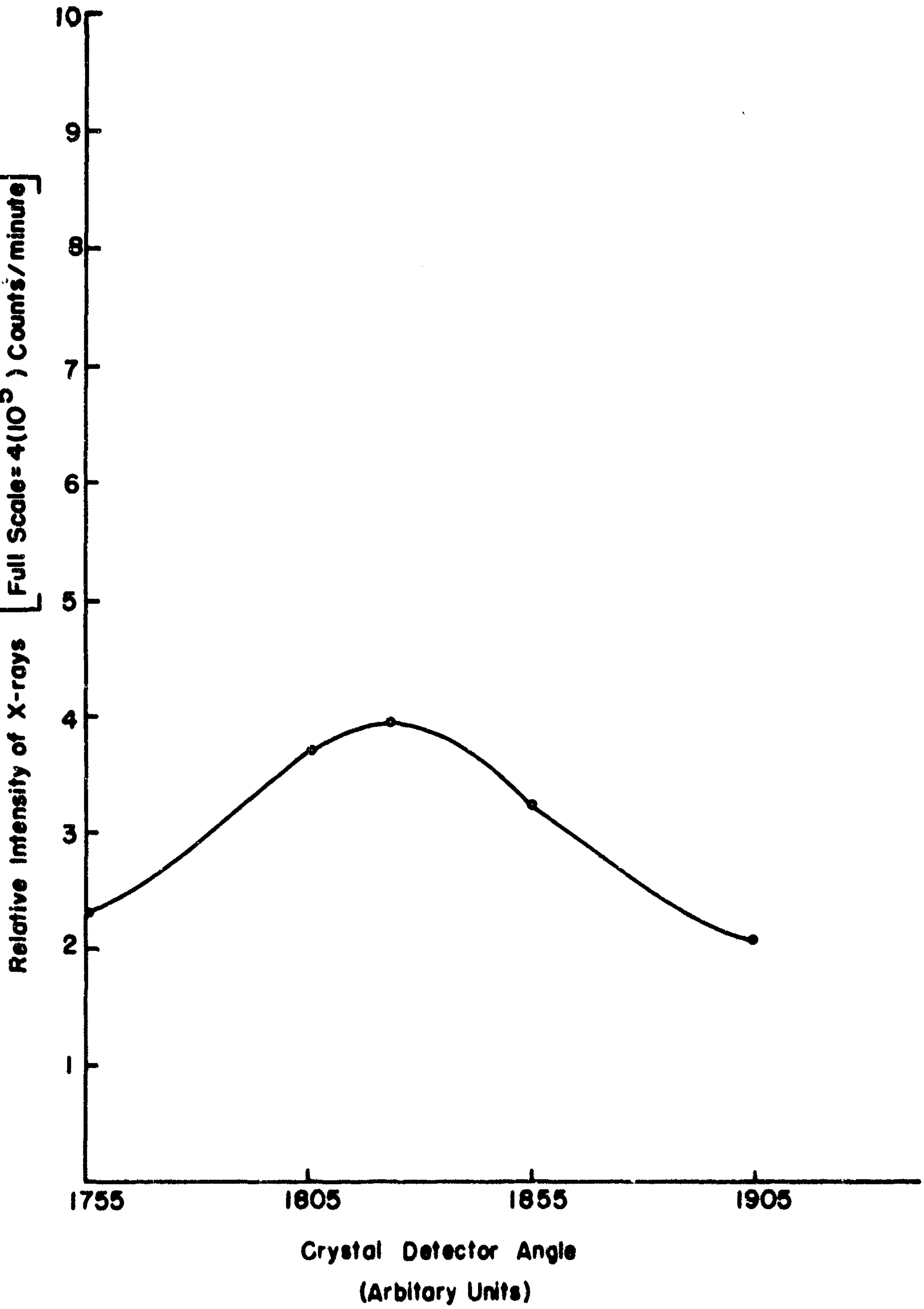


Fig. 3.1433 Microprobe Response From Pyrex Glass

IV illustrates the effects of time and temperature on the soldered type of terminations. Plate V provides comparison of test panels (as opposed to an individual terminal pad of the high and low temperature groups. Plate V also illustrates the manner in which the test panels were mounted in the oven chambers.

3.22 Statistical Analysis

The frequency of occurrence of values of ΔR was plotted in histogram form for several resistor categories. The resulting histograms, which utilize only those values of ΔR between .900 and 1.100, indicate an approximately gaussian normal distribution in all cases. Using a histogram based on values of ΔR from all categories, overall experimental accuracy is placed at $\pm$ 7% ($\pm$ 3 σ). These histograms are contained in the Appendix.

3.23 Plots of < ΔR >

Plots of averaged values of ΔR for the 175°C and the 125°C coated and non-coated categories are contained in the Appendix. The following observations are made from these plots. At 175°C, it was found that ΔR, coated category, remained constant at about .975 while ΔR, non-coated category, gives indications of increasing approximately 12.4% per decade of time after 400 hours of operation After approximately 400 hours of operation, resistors of the non-coated high temperature category increased in value faster than those resistors in the non-coated low temperature category. No significant difference was indicated between the coated resistors at 175°C and those at 125°C. All averages include only those values of ΔR between 0.900 and 1.100.

3.3 Data Summary

1. Neglecting process A_1 failures, plots of ΔR show that all on-test catastrophic failures were of the unprotected, welded termination, type NC-C_2.
2. Eight of the nine recorded open terminations from final bridge measurements were of the unprotected welded catagory.
3. Both failures shown by the cooling curves were of the unprotected welded termination, type NC-C_2.
4. Catastrophic failures cannot be attributed to the resistive cermet material.
5. Electron microprobe analysis indicates abnormally high oxygen content on those portions of terminal pad copper not over-laid with SiO.
6. Histrograms indicate gaussian normal distribution of measurements and place overall experimental accuracy at $\pm$ 7%.

4.0 Conclusions and Recommendations

The conclusions which might logically be drawn from these tests must be tempered by several considerations. For example, of the total of 28 failures encountered in these tests, 6, or almost 25% are accounted for by process A_1. This process was used for the control group, and, it is presumed, should have provided failure-free standards to which failures could be compared. Failure of these units is not attributable to the process, however, but rather to the method of lead wire attachment. The contract intent for the control group (all 10-6-n) units was that the terminations be welded, and that some would be covered with protective coat while others would be left unprotected. The actual termination methods used for the control group were C_3 and C_4 soldering either to the tinned pad or by localized soldering. During the soldering process, it is likely that the eutectic solder took into solution much (perhaps nearly all) of the gold termination pad, leaving a rather questionable contact between lead wire and resistive element. It is also possible that due to small thermal gradients in the ovens, some of the pads could have reached eutectic temperature of the solder and continued to leach out gold such that electrical contact resistance increased drastically with exposure time to high temperatures. Visual observation of the pads confirms that gold pad area has been reduced significantly in many cases. It is thus concluded that test failures of all A_1 units resulted from lead attachment methods and are not indicative of ultimate capabilities of this class of thin-film resistors.

Ignoring the control panel failures (as remaining conclusions will), only one failure can be attributed to a coated terminal--this a drift failure of 10-1-1 R_6, process A, termination method C_3. Failures according to termination types are:

C_1 - 6 (all high temp. -4 process B, 2 process A)

C_2 - 12 (two low temp. process A; 5 process A, 5 process B at high temp.)

C_3 - 1 (high temperature, process A)

C_4 - 3 (all high temp. - 2 process A, 1 process B)

It can be concluded from these data that termination process C_3, soldering to the tinned termination pad, is the most desirable of the four used. Processes C_1 and C_4 are equally less desirable, with C_2 least desirable of all since it accounts for half the failures.

Comparison of the 12 failures from process A and the 10 failures from process B suggests no important failure-contribution differences between the processing methods.

The microprobe data indicates that the primary failure mechanism is oxidation of the copper pads and subsequent loss of low-resistance electrical contact to the cermet element. The oxidation process would proceed most rapidly in the case of leads welded in the manner of C-2 and less rapidly with the localized soldering because of some limited protection from oxidizing effects of the environment. Method C_1 leaves the termination open to oxidation; however, welding just above the cermet element, might possibly give a stronger weld. Termination

method C-3 provides a protective overcoating of tin such that the oxidation rate over the entire pad is quite low, thus yielding the low failure rate of this termination method.

Since unprotected (N-C) terminals account for 21 of the 22 failues, it must be concluded that the Sylgard 182 significantly reduces the oxidation rate. It can not be concluded at this point that the Sylgard protection is as effective as the tinned terminal in preventing oxidation. Modification of the lead-tin content in the solder can increase the usable temperature of the soldered terminal significantly if this termination method is found to be most suitable.

Opportunities for future work can be found in several areas related to the present study. First, more lengthy tests are needed to establish whether the Sylgard 182 is a significant protective covering or merely delays the ultimate failure for a few hundred or thousand hours. The same question might be raised for the solder-tinned pad type of termination. Additional studies might be made with welded terminations to determine effects of varying maximum temperatures reached during the weld cycle and the effects of various pre-weld terminal cleaning procedures. A more complete analysis by electron microprobe of several cross-sectioned terminations of new and failed units should provide a metallurgical profile of the pad area and might yield significant new data.

APPENDIX

TABLE A_{T1}

ON-TEST DATA SUMMARY
LOW TEMPERATURE TEST (125°C)

		10 - 2 - 2							
DATE	HOURS	ΔR_1	ΔR_2	ΔR_3	ΔR_4	ΔR_5	ΔR_6	ΔR_7	ΔR_8
6/ 6	0	1.079	1.040	1.015	1.023	.9497	.9631	.9564	.9648
6/ 6	1	.9962	.9992	.9748	.9767	.9497	.9631	.9471	.9434
6/ 6	5.5	.9978	1.001	.9824	.9262	.9478	.9631	.9510	.9392
6/ 7	22.6	.9978	1.001	.9824	.9883	.9517	.9884	.9655	.9636
6/ 7	24.75	.9811	.9840	.9588	.9610	.9547	.9615	.9495	.9481
6/ 8	47.92	.9271	.9507	.9289	.9392	.9617	.9752	.9591	.9481
6/ 9	71.58	.9412	.9716	.9360	.9440	.9497	.9769	.9471	.9398
6/10	95.83	.9412	.9716	.9360	.9440	.9497	.9404	.9471	.9398
6/13	167.8	.9563	.9662	.9414	.9320	.9517	.9510	.9400	.9458
6/18	288.1	.9530	.9700	.9409	.9514	.9687	.9890	.9591	.9517
6/22	389.4	.9039	.9202	.9056	.9158	.9402	.9664	.9285	.9904
6/23	412.9	1.026	1.003	.9777	.9872	.9857	.9840	.9707	.9686
6/27	509.7	1.194	1.018	1.148	1.007	1.006	.8806	1.050	.9821
6/28	533.7	.9568	.9594	.9391	.9491	.9777	1.000	.9719	.9615
7/ 1	580.5	.9568	.9594	.9371	.9491	.9497	.9785	.9544	.9403
7/ 5	687.5	.9676	.9705	.9500	.9600	.9668	.9895	.9694	.9540
7/ 8	754.5	.9530	.9700	.9445	.9514	.9567	.9631	.9471	.9434
7/12	850	1.021	.9948	.9765	.9900	.9777	.9925	.9870	.9780
8/11	1014	.9887	.9957	.9795	.9813	.9980	.9901	.9805	.9701
8/13	1060	.9843	.9981	.9887	.9883	.9818	.9868	.9844	.9813
8/15	1110	.9854	.9908	.9713	.9766	.9913	.9901	.9895	.9804
8/17	1157	.9865	.9897	.9663	.9795	.9824	.9741	.9557	.9507
8/19	1206	.9773	.9673	.9605	.9636	.9894	.9774	.9672	.9678
8/21	1252	.9682	.9770	.9639	.9679	.9874	.9659	.9627	.9691
8/23	1304	.9736	.9700	.9639	.9756	.9838	.9796	.9709	.9698
8/25	1350	.9725	.9624	.9556	.9588	.9807	.9730	.9627	.9621
8/27	1400	.9763	.9724	.9690	.9663	.9603	.9659	.9627	.9697
		$C-C_2$	$C-C_3$	$C-C_1$	$C-C_4$	$NC-C_2$	$NC-C_3$	$NC-C_1$	$NC-C_4$

TABLE A_{T1} CONT.

DATE	HOURS	10 - 1 - 5 ΔR_1	ΔR_2	ΔR_3	ΔR_4	ΔR_5	ΔR_6	ΔR_7	ΔR_8
6/ 6	0	1.014	1.006	1.022	1.078	.9800	.9670	1.002	.9974
6/ 6	1	1.028	.9780	1.008	1.010	.9709	.9702	.9651	.9808
6/ 6	5.5	1.024	.9837	.9870	.9994	.9811	1.013	.9687	.9761
6/ 7	22.6	1.031	.9797	.9983	1.013	.9777	.9921	.9787	.9783
6/ 7	24.75	1.004	.9675	.9707	.9774	.9494	.9568	.9456	.9416
6/ 8	47.92	.9601	.9236	.9401	.9508	.9494	.9622	.9427	.9305
6/ 9	71.58	.9736	.9439	.9506	.9607	.9777	.9702	.9651	.9561
6/10	95.83	.9442	.9285	.9347	.9445	.9767	.9890	.9623	.9514
6/13	167.83	.9904	.9715	.9648	.9803	.9854	.9702	.9704	.9667
6/18	288.1	.9307	.9374	.9473	.9560	.9767	.9756	.9574	.9514
6/22	389.4	.9772	.9146	.9209	.9398	.9767	.9890	.9574	.9514
6/23	412.9	.9772	.9455	.9477	.9682	.9683	.9753	.9610	.9471
6/27	509.7	.9228	1.440	5.799	1.482	1.101	.9080	1.091	1.050
6/28	533.7	.9871	.9553	6.128	.9780	.9811	.9788	.9645	.9821
7/ 1	580.5	.9751	.9333	12.56	.9641	.9580	1.023	.9462	.9714
7/ 5	687.5	.9877	.9293	16.54	.9503	.9700	1.017	.9663	.9655
7/ 8	754.5	.9697	.9504	24.63	.8884	.9546	.9702	.9498	.9441
7/12	850	1.037	.9146	39.77	.9254	.9889	1.004	.9775	.9407
8/11	1014								
8/13	1060								
8/15	1110								
8/17	1157								
8/19	1206								
8/21	1252								
8/23	1304								
8/25	1350								
8/27	1400								
		$NC-C_1$	$NC-C_3$	$NC-C_2$	$NC-C_4$	$C-C_2$	$C-C_1$	$C-C_3$	$C-C_4$

TABLE A_{T1} CONT

DATE	HOURS	10 - 6 - 1 ΔR_3	10 - 6 - 1 ΔR_4	10 - 6 - 1 ΔR_5	10 - 6 - 1 ΔR_8	10 - 6 - 5 ΔR_1	10 - 6 - 5 ΔR_3	10 - 6 - 5 ΔR_5	10 - 6 - 5 ΔR_7
6/ 6	0	1.009	1.023	1.006	1.013	.9817	.9996	.9992	1.012
6/ 6	1	.9478	.9612	.9650	.9849	.9363	.9913	.9827	.9952
6/ 6	5.5	.9604	.9735	.9784	.9724	.9800	.9992	.9589	.9864
6/ 7	22.6	.9408	1.004	.9374	1.009	.9349	.9992	.9696	.9972
6/ 7	24.75	.9711	.9688	.9693	.9849	.9438	.9738	.9624	.9870
6/ 8	47.92	.9774	.9544	.9477	.9849	.9349	.9583	.9681	.9448
6/ 9	71.58	.9639	.9615	.9477	.9849	.9363	.9766	.9600	.9585
6/10	95.83	.9497	.9475	.9477	.9955	.9363	.9792	1.023	.9723
6/13	167.83	.96[illegible]	.9683	.9477	1.006	.9817	.9896	.9950	.9785
6/18	288.1	.9785	.9621	1.007	1.012	.9817	.9766	.9754	.9657
6/22	389.4	.9743	.9337	.9844	.9782	.9817	.9660	.9738	.9310
6/23	412.9	.9907	.9925	.9679	1.002	.9640	.9766	.9692	.9870
6/27	509.7	1.105	1.132	.9215	1.052	.8933	1.083	.9897	1.060
6/28	533.7	.9722	.9711	.9738	1.006	.9696	.9858	.9730	.9785
7/ 1	580.5	.9686	.9584	.9738	1.006	.9630	.9789	.9730	.[illegible]35
7/ 5	687.5	.9815	.9836	.9804	1.013	.9696	.9858	.9730	.9785
7/ 8	754.5	.9785	.9761	.9775	1.016	.9438	.9871	.9681	.9585
7/12	850	.9983	.9922	.9630	1.048	.9752	1.020	.9714	1.003
8/11	1014			.9878	1.017	.9551	.9870	.9535	.9607
8/13	1060			1.005	1.036	.9434	.9865	.9719	.9644
8/15	1110			.9673	.9742	.9719	1.000	.9719	.9822
8/17	1157			.9667	1.013	.9752	.9870	.9784	.9769
8/19	1206			.9829	1.011	.9771	1.000	.9538	.9703
8/21	1252			.9682	1.014	.9658	1.003	.9689	.9578
8/23	1304			.9750	1.026	.9644	.9970	.9670	.9661
8/25	1350			.9795	1.014	.9759	.9862	.9768	.9776
8/27	1400			.9821	1.012	.9611	.9983	.9727	.9657
		NC-C_3	NC-C_4	C-C_4	C-C_3	C-C_4	C-C_3	NC-C_3	NC-C_4

TABLE A_{T1} CONT.

		10 - 3 - 4		10 - 3 - 5		10 - 1 - 3		10 - 4 - 5	
DATE	HOURS	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}
6/ 6	0	.9941	.9920	.9948	.978	1.016	1.003	1.010	.968
6/ 6	1	.9696	.9510	.9736	.978	1.004	.989	.9944	.968
6/ 6	5.5	.9879	.9870	1.064	1.013	.9884	1.013	.9944	.992
6/ 7	22.6	1.003	.9940	1.019	1.029	1.017	1.022	1.000	1.008
6/ 7	24.75	.9949	.9790	.9857	.978	.9852	1.002	.9767	.967
6/ 8	47.92	.9928	.9960	.9894	.990	.9852	1.015	.9783	.967
6/ 9	71.58	.9733	.947	.9593	.961	.9723	.982	.9628	.959
6/10	95.83	.9733	.989	.9770	.978	.9796	.989	.9628	.952
6/13	167.8	.9840	.989	.9788	.978	.9868	.989	.9787	.960
6/18	288.1	.9771	.981	.9435	.975	.9453	.989	.9551	.960
6/22	389.4	.9683	.998	.9368	.964	.9650	1.002	.9250	.960
6/23	412.9	.9789	.974	.9711	.964	.9700	.998	.9656	.956
6/27	509.7	1.001	1.008	1.075	1.004	1.103	1.052	1.100	1.029
6/28	533.7	.9797	.959	.9716	.955	.9746	1.007	.9465	.953
7/ 1	580.5	.9797	.959	.9716	.955	.9746	1.007	.9531	.959
7/ 5	687.5	.9797	.959	.9953	.974	.9861	1.018	.9735	.965
7/ 8	754.5	.9882	.992	.9822	.962	.9852	1.001	.9634	.968
7/12	850	1.073	1.008	.9877	.967	1.025	1.028	.9626	.959
8/11	1014	.9909	.9903	.9963	.9727	1.001	1.011	.9795	.9704
8/13	1060	.9912	.9886	1.003	.9910	.9931	1.003	.9696	.9817
8/15	1110	.9840	.9935	1.003	.9845	1.010	1.031	.9767	.9746
8/17	1157	.9843	.9825	.9793	.9809	.9931	1.019	.7848	.9793
8/19	1206	.9762	.9774	.9825	.9774	.9848	1.010	.9795	.9700
8/21	1252	.9813	.9771	.9983	.9722	.9784	1.001	.9795	.9700
8/23	1304	.9893	.9757	.9911	.9794	.9876	1.022	.9769	.9823
8/25	1350	.9888	.9961	.9983	.9787	.9905	1.015	.9688	.9734
8/27	1400	.9949	.9917	.9998	.9739	.9931	1.015	.9686	.9659
		C	NC	NC	C	C	NC	C	NC

TABLE A_{T1} CONT.

		10 - 2 - 8		10 - 4 - 7	
DATE	HOURS	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}
6/ 6	0	1.028	.959	1.010	1.012
6/ 6	1	.9867	.959	.9857	.973
6/ 6	5.5	.9821	.979	.9757	.985
6/ 7	22.6	.9727	.979	.9935	1.002
6/ 7	24.75	.9658	.952	.9650	.973
6/ 8	47.92	.9658	.959	.9650	.973
6/ 9	71.58	.9462	.945	.9650	.943
6/10	95.83	.9658	.952	.9412	.943
6/13	167.8	.9542	.947	.9561	.949
6/18	288.1	.9518	.957	.9382	.954
6/22	389.4	.9393	.952	.9311	.954
6/23	412.9	.9367	.926	.9305	.932
6/27	509.7	1.101	1.017	1.129	1.059
6/28	533.7	.9453	.927	.9632	.968
7/ 1	580.5	.9574	.936	.9424	.951
7/ 5	687.5	1.410	.962	.9632	.972
7/ 8	754.5	1.607	.962	.9650	.973
7/12	850	1.902	.975	.9745	.958
8/11	1014				.9800
8/13	1060				.9845
8/15	1110				.9731
8/17	1157				.9747
8/19	1206				.9898
8/21	1252				.9760
8/23	1304				.9766
8/25	1350				.9778
8/27	1400				.9731
		NC	C	NC	C

TABLE A_{T2}

ON-TEST DATA SUMMARY SHEET
HIGH TEMPERATURE TEST (175°C)

DATE	HOURS	10 - 3 - 8							
		ΔR_1	ΔR_2	ΔR_3	ΔR_4	ΔR_5	ΔR_6	ΔR_7	ΔR_8
7/14	0	.9826	.9780	.9757	.9830	.9887	1.009	.9814	.9744
7/17	72	.9669	.9959	.9893	.9913	.9792	.9664	.9793	.9703
7/17	80	.9673	.9691	.9649	.9801	.9683	.9846	.9703	.9657
7/18	96	.9826	.9780	.9757	.9756	.9887	1.009	.9814	.9744
7/19	120	1.003	1.020	.9873	.9930	1.015	1.045	.9976	.9862
7/21	168								
7/23	216	.9456	.9802	.9671	.9664	.9773	.9392	.9670	.9638
7/26	288	.9567	.9917	.9785	.9778	.9982	.9499	.9834	.9786
7/29	360	.9456	.9802	.9671	.9716	.9758	.9286	.9665	.9604
8/	480	.9456	.9802	.9671	.9716	.9869	.9392	.9775	.9713
8/ 5	504	.9401	.9745	.9652	.9711	.9650	.9412	.9557	.9570
8/ 8	576	.9703	1.831	.9706	.9952	.9914	.9536	.9655	.9681
8/11	648	.9967	.9599	.9702	.9924	.9671	.9682	.9558	.9569
8/13	693	.9898	.9529	.9635	.9906	.9654	.9638	.9535	.9586
8/15	742	.9913	.9545	.9610	.9870	.9663	.9671	.9549	.9596
8/17	790	1.008	.9653	.9712	1.008	.9882	.9800	.9623	.9648
8/19	839.5	.9051	.8653	.8823	.9550	.9857	.9777	.9600	.9629
8/21	884	1.003	.9620	1.062	1.072	.9789	.9845	.9623	.9612
8/23	936	1.001	.9636	1.074	1.060	.9654	.9640	.9609	.9589
8/25	980	1.015	.9620	1.071	1.070	.9916	.9835	.9623	.9632
8/27	1030	1.003	.9645	1.056	1.072	.9857	.9777	.9650	.9629
8/30	1095	1.006	.9620	1.066	1.076	.9823	.9762	.9706	.9681
8/31	1139	.9972	.9949	1.069	1.062	.9646	.9603	.9558	.9556
		NC-C_4	NC-C_3	NC-C_1	NC-C_2	C-C_3	C-C_4	C-C_1	C-C_2

TABLE A_{T2} CONT.

DATE	HOURS	10 - 1 - 1 ΔR_1	ΔR_2	ΔR_3	ΔR_4	ΔR_5	ΔR_6	ΔR_7	ΔR_8
7/14	0	1.009	.9823	.9875	.9813	.9690	.9114	.9800	983
7/17	72	1.018	.9921	1.000	1.007	.9741	.9268	.9923	.9915
7/17	80	1.019	1.003	.9876	.9894	.9802	.9208	.9776	.9769
7/18	96	1.634	.9822	.9875	.9813	.9713	.9136	.9824	.9834
7/19	120	.9972	.9670	.9347	.9504	.9695	.9231	.9623	.95[illegible]
7/21	168								
7/23	216	.9886	.9734	.9558	.9623	.9611	.9675	.9690	.9633
7/26	288	.9972	.9819	.9641	.9707	.9756	.9695	1.002	.97[illegible]
7/29	360	.9886	.9734	.9[illegible]95	.9674	.9685	1.019	.9740	9708
8/ 3	480	.9972	.9819	.9752	.9809	.9770	1.028	.9825	.9793
8/ 5	504	.8798	1.339	12.69	.9910	.9459	1.003	.9636	.9532
8/ 8	576	1.159	1.015	19.83	1.022	.9610	.9895	.9666	.9906
8/11	648	.9976	1.032	24.88	.9812	.9365	1.031	.9590	.9528
8/13	693	1.009	1.053	28.1	.9842	.9365	1.151	1.155	.9502
8/15	742	1.004	1.077	30.56	.9684	.9374	1.181	.9651	.9572
8/17	790	1.020	1.096	31.51	1.004	.9443	1.209	.9592	.9642
8/19	839.5	.9985	1.101	35.68	.9813	.9314	1.203	.9441	.9572
8/21	884	1.002	1.084	36.07	.9807	.9314	1.211	.9511	.9515
8/23	936	.9953	1.088	36.57	.9912	.9485	1.194	.9540	.9690
8/25	980	1.006	1.084	36.90	.9860	.9374	1.211	.9552	.9515
8/27	1030	.9988	1.085	36.90	.9930	.9383	1.211	.9552	.9515
8/30	1095	1.002	1.080	38.47	.9731	.94[illegible]3	1.220	.9621	.9550
8/31	1139	1.004	1.080	40.46	.9877	.9545	1.226	.9621	.9590
		NC-C_1	NC-C_4	NC-C_2	NC-C_3	C-C_1	C-C_3	C-C_4	C-C_2

TABLE A_{T2} CONT.

		10 - 6 - 2				10 - 6 - 6			
DATE	HOURS	ΔR_3	ΔR_4	ΔR_5	ΔR_8	ΔR_3	ΔR_4	ΔR_6	ΔR_7
7/14	0	.9842	1.026	.9725	.9668	.9807	.9856	.9445	1.103
7/17	72	1.180	1.182	1.161	1.118	.9829	.9714	.9621	1.024
7/17	80	.9312	.9487	.9411	.9329	.9607	.9894	.8999	1.040
7/18	96	.9842	1.026	.9725	.9668	.9870	.9856	.9445	1.103
7/19	120	.9243	.9592	.9198	.9144	.9181	.9287	.9325	1.075
7/21	168								
7/23	216	.9705	1.021	.9636	.9580	.9870	1.025	.9478	1.135
7/26	288	.9563	.9961	.9837	.9680	.9870	1.025	.9931	1.119
7/29	360	.9802	1.048	.9837	.9680	.9494	.9765	.8979	1.103
8/ 3	480	.9802	1.034	.9871	.9916	.9629	1.000	1.020	1.150
8/ 5	504	.9608	1.062	.9636	.9680	.9672	1.065	1.020	1.193
8/ 8	576	.9802	1.159	1.006	1.690	.9558	1.278	1.020	1.266
8/11	648	1.021	15.44	.9817	2.146	.9754	1.307	1.034	1.274
8/13	693	.9584	9.720	.9692	3.083	.9724	1.098	1.013	1.267
8/15	742	.9739	8.13	.9857	3.724	1.128	1.082	1.025	1.281
8/17	790	.9688	8.11	.9865	4.16	.9727	.9940	1.062	1.294
8/19	839.5	.9720	7.83	1.000	5.04	.9759	1.202	.9383	1.297
8/21	884	.9689	7.735	.9913	5.000	.9822	1.008	.9994	1.301
8/23	936	.9779	9.180	.9927	5.717	1.645	1.105	1.078	1.297
8/25	980	.9837	9.235	.9941	5.675	1.734	1.157	1.087	1.318
8/27	1030	.9608	9.514	.9789	5.972	1.743	1.201	1.107	1.324
8/30	1095	.9769	10.35	.9798	6.119	1.800	1.225	3360.0	1.317
8/31	1139	.9786	10.20	.9966	6.236	1.844	1.388	3110.0	1.198
		$C-C_4$	$C-C_3$	$NC-C_4$	$NC-C_3$	$NC-C_4$	$NC-C_3$	$C-C_4$	$C-C_3$

TABLE A_{T2} CONT.

		10 - 2 - 4		10 - 3 - 7		10 - 1 - 7		10 - 2 - 6	
DATE	HOURS	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}	ΔR_{14}	ΔR_{58}
7/14	0	.9736	.9744	.9760	.9716	1.001	.9731	.9969	.9938
7/17	72	1.034	.9318	.9754	.9682	.8996	1.020	.9290	1.013
7/17	80	.9608	1.003	.9754	.9682	.9592	.9383	.9715	.9697
7/18	96	.9736	.9744	.9760	.9563	1.001	.9731	.9969	.9938
7/19	120	.9700	.9664	.9564	.9638	.9586	.9301	.9339	.9487
7/21	168								
7/23	216	.9448	1.007	.9646	.9720	.9869	.9331	.9682	.9702
7/26	288	.9572	.9533	.9646	.9720	.9728	.9197	.9610	.9630
7/29	360	.9590	.9677	.9613	.9689	.9595	.9098	.9514	.9795
8/ 3	480	.9588	.9484	.9581	.9771	.9595	.9331	.9493	.9403
8/ 5	504	.9725	.9493	.9501	.9690	.9595	.9576	.9493	.9523
8/ 8	576	3.845	.9451	.9597	.9681	.9604	.9599	.9530	.9694
8/11	648	5.212	.9465	.9679	.9611	.9793	1.155	.9691	1.019
8/13	693	5.791	.9415	.9659	.9636	.9807	1.217	.9631	1.311
8/15	742	6.492	.9385	.9672	.9713	.9730	1.230	.9623	1.401
8/17	790	6.848	.9448	.9609	.9690	.9675	1.273	.9540	1.464
8/19	839.5	7.06	.9445	.9563	.9689	.9702	1.311	.9509	1.531
8/21	884	7.20	.9467	.9576	.9661	.9752	1.303	.9462	1.592
8/23	936	7.603	.9413	.9703	.9851	.9782	1.316	.9624	1.621
8/25	980	7.174	.9470	.9553	.9710	.9677	1.324	.95[illegible]	1.661
8/27	1030	8.083	.9344	.9490	.9724	.9752	1.324	.9504	1.675
8/30	1095	8.341	.9421	.9631	.9710	.9752	1.345	.9582	1.733
8/31	1139	8.627	.9284	.9705	.97[illegible]	.9821	1.337	.9498	1.727
		NC	C	C	NC	C	NC	C	NC

TABLE A_{T2} CONT.

DATE	HOURS	10 - 4 - 4 ΔR_{14}	10 - 4 - 4 ΔR_{58}	10 - 4 - 3 ΔR_{14}	10 - 4 - 3 ΔR_{58}
7/14	0	.9939	.9595	.9968	.9294
7/17	72	.9784	.9689	.9742	1.034
7/17	80	.9867	.9608	.9749	.9743
7/18	96	.9939	.9595	.9768	.9694
7/19	120	.9829	.9473	.9768	.9861
7/21	168				
7/23	216	.9773	.9481	.9570	.9678
7/26	288	.9854	.9560	.9627	.9678
7/29	360	.9816	.9524	.9721	.9782
8/ 3	480	.9816	.9524	.9646	.9710
8/ 5	504	.9757	.9412	.9721	.9599
8/ 8	576	1.027	.9447	1.018	.9770
8/11	648	1.035	.9507	1.029	.9657
8/13	693	1.035	.9506	1.004	.9625
8/15	742	1.043	.9507	1.040	.9661
8/17	790	1.030	.9388	1.034	.9632
8/19	839.5	1.039	.9520	1.031	.9654
8/21	884	1.043	.9533	1.049	.9708
8/23	936	1.052	.9475	1.043	.9670
8/25	980	1.066	.9554	1.050	.9676
8/27	1030	1.063	.9566	1.048	.9664
8/30	1095	1.060	.9478	1.055	.9733
8/31	1139	1.067	.9516	1.048	.9650
		C	NC	NC	C

TABLE A_{T3}
LOW TEMPERATURE TEST (125°C)
RESISTANCE BRIDGE MEASUREMENTS

PANEL 10-1-5				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	626.7	639		1.020
R_2	1189	1196		1.006
R_3	2389	1.71×10^5		71.58
R_4	1729	1764		1.020
R_5	1167	1175		1.007
R_6	618.4	628		1.016
R_7	1692	1712		1.012
R_8	2345	2372		1.012

PANEL 10-2-2				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	1853	1847	1850	.9984
R_2	3695	3697	3700	1.001
R_3	7260	7256	7269	1.001
R_4	5460	5453	5461	1.000
R_5	3580	3583	3590	1.003
R_6	5332	5333	1808	.9950
R_7	6996	6995	5340	1.001
R_8	1817	1802	7094	1.014

PANEL 10-6-1				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_3	7200	7296		
R_4	5355	5486	5506	1.028
R_5	3517	3553	3565	1.014
R_8	7077	7560	7610	1.075

PANEL 10-6-5				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	2136	2090	2138	1.001
R_3	7680	7810	7918	1.031
R_5	3700	3724	3749	1.013
R_7	5450	5450	5461	1.002

TABLE A_{T3} CONT.

PANEL 10-2-8				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	946	948		1.002
R_2	1876	1872		.9979
R_3	3860	3916		1.015
R_4	2913	$7.3x10^5$		25.06
R_5	1808	1808		1.000
R_6	923	926		1.003
R_7	2855	2854		1.000
R_8	3775	3777		1.000

PANEL 10-4-7				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	1355	1365	1357	1.001
R_2	3137	3288	3143	1.002
R_3	7242	7572		
R_4	5110	5412	5142	1.006
R_5	3122	3136	3125	1.001
R_6	1282	1306	1286	1.003
R_7	5135	5154	5150	1.003
R_8	7160	7280	7292	1.018

PANEL 10-3-4				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	496	501	503.3	1.015
R_2	1208	1217	1220	1.010
R_3	2640	2676	2690	1.019
R_4	1910	1929	1937	1.014
R_5	1192	1202	1203	1.009
R_6	495	506	503.9	1.018
R_7	1888	1896	1901	1.007
R_8	2587	2615	2628	1.016

PANEL 10-3-5				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	327	331	332	1.015
R_2	780	787	799.3	1.025
R_3	1700	1764	1790	1.053
R_4	1243	1258	1266	1.018
R_5	767.5	771	772	1.006
R_6	319	322	323.5	1.014
R_7	1221	1232	1236	1.012
R_8	1681	1703	1710	1.017

PANEL 10-1-3				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	963	979	982.5	1.020
R_2	1855	1874	1880	1.013
R_3	3622	3665	3684	1.017
R_4	2627	2653	2668	1.016
R_5	1780	1797	1803	1.013
R_6	904	917	919.1	1.017
R_7	2610	2633	2646	1.014
R_8	3598	3636	3690	1.026

PANEL 10-4-5				
RES.	BRIDGE MEASUREMENTS			ΔR_f
	INITIAL	850 HOURS	FINAL	
R_1	443	443	443.5	1.001
R_2	970	968	969.4	.9994
R_3	2095	2095	2099	1.002
R_4	1520	1520	1522	1.001
R_5	954	954	956.7	1.003
R_6	423	429	433.5	1.025
R_7	1493	1524	1528	1.023
R_8	2057	2056	2060	1.001

TABLE A_{T4}

HIGH TEMPERATURE TEST (175°C)
RESISTANCE BRIDGE MEASUREMENTS

PANEL 10-1-1			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
1	593		
R_2	1169	1297	1.109
R_3	2363	BIT	
R_4	1711	1774	1.037
R_5	1166	1161	.9957
R_5	659.4	876.0	1.328
R_7	1717	1731	1.008
R_8	2291	2315	1.010

PANEL 10-3-8			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	491.9	BIT	
R_2	1210	1221	1.009
R_3	3126	BIT	
R_4	2238	BIT	
R_5	1186	1199	1.011
R_6	484.0	486.8	1.006
R_7	2174	2193	1.009
R_8	3042	3076	1.011

BIT = Lead Broken In Test

PANEL 10-6-2			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_3	25,760	25,830	1.003
R_4	18,120	20,000	1.104
R_5	11,860	12,210	1.030
R_8	23,860	100,000	4.191

PANEL 10-6-6			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_3	25,330	152,000	6.001
R_4	18,530	149,300	8.057
R_6	7620	870,000	114.0
R_7	19,080	25,950	1.360

TABLE A_{T4} CONT.

PANEL 10-2-4			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	921.5	923	1.002
R_2	1825	2791	1.529
R_3	3621	28400	7.843
R_4	2739	2791	1.019
R_5	1881	1951	1.037
R_6	979.9	980	1.000
R_7	2819	2832	1.005
R_8	3711	3605	.9714

PANEL 10-4-3			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	658.6	910	1.382
R_2	1507	1570	1.042
R_3	3215	3244	1.009
R_4	2290	BIT	
R_5	1409	1413	1.003
R_6	605.4	610.7	1.009
R_7	2173	2189	1.007
R_8	3046	3060	1.005

PANEL 10-4-4			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	631.4	632	1.002
R_2	1446	1454	1.006
R_3	3160	3181	1.007
R_4	2275	2287	1.005
R_5	1473	1480	1.005
R_6	641.5	935	1.458
R_7	2323	BIT	
R_8	3212	3269	1.018

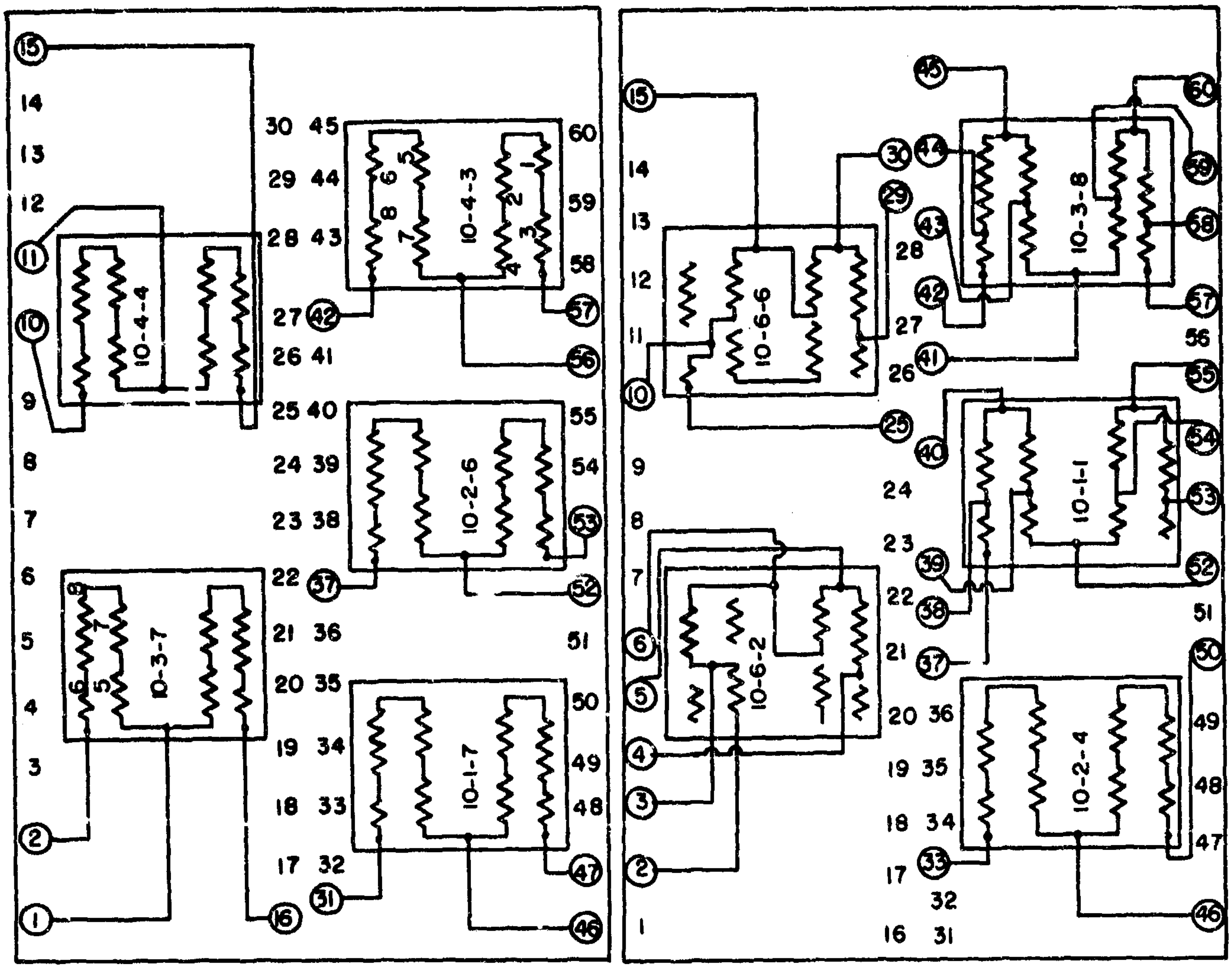
PANEL 10-3-7			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	1012	1028	1.016
R_2	2463	2490	1.011
R_3	6580	6641	1.009
R_4	4533	4565	1.007
R_5	2420	BIT	
R_6	961.3	980	1.019
R_7	4476	4586	1.025
R_8	6293	6485	1.032

PANEL 10-1-7			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	2358	2387	1.012
R_2	4101	4142	1.010
R_3	8000	8066	1.008
R_4	5690	5738	1.008
R_5	3739	3751	1.003
R_6	2053	2099	1.022
R_7	5714	160,400	28.07
R_8	7620	7678	1.008

PANEL 10-2-6			
RES.	BRIDGE MEASUREMENTS		ΔR_f
	INITIAL	FINAL	
R_1	1966	1858	.9451
R_2	3821	3873	1.014
R_3	7619	7626	1.001
R_4	5742	5769	1.005
R_5	3649	BIT	
R_6	1927	2122	1.101
R_7	5514	BIT	
R_8	7246	7255	1.001

FIGURE A_1

HIGH TEMPERATURE TEST WIRING DIAGRAM



TERMINAL LUG #	TEST CIRCUIT	SOLDER LUG #
4-7	10-3-7	1
4-8	10-3-7	2
4-6	10-3-7	16
6-4	10-4-4	10
6-3	10-4-4	11
6-2	10-4-4	15
5-4	10-1-7	31
5-3	10-1-7	46
5-2	10-1-7	47
5-8	10-2-6	37
5-7	10-2-6	52
5-6	10-2-6	53
6-8	10-4-3	42
6-7	10-4-3	56
6-6	10-4-3	57
TERMINAL LUG #	**TEST CIRCUIT**	**SOLDER LUG #**
3-4	10-6-6	25
3-5	10-6-6	10
Grnd	10-6-6	15
3-6	10-6-6	30
3-2	10-6-6	29
3 10	10-6-2	2
3-11	10-6-2	3
Grnd	10-6-2	6
3-12	10-6-2	5
3-8	10-6-2	4
4-4	10-2-4	33
4-3	10-2-4	46
4-2	10-2-4	50
2-8	10-1-1	37
2-9	10-1-1	38
2-10	10-1-1	40
2-11	10-1-1	39
2-6,12	10-1-1	52
2-5	10-1-1	54
2-4	10-1-1	55
2-3	10-1-1	53
2-2	10-1-1	--
1-8	10-3-8	42
1-9	10-3-8	44
1-10	10-3-8	45
1-11	10-3-8	43
1-6,12	10-3-8	41
1-5	10-3-8	59
1-4	10-3-8	60
1-3	10- -8	58

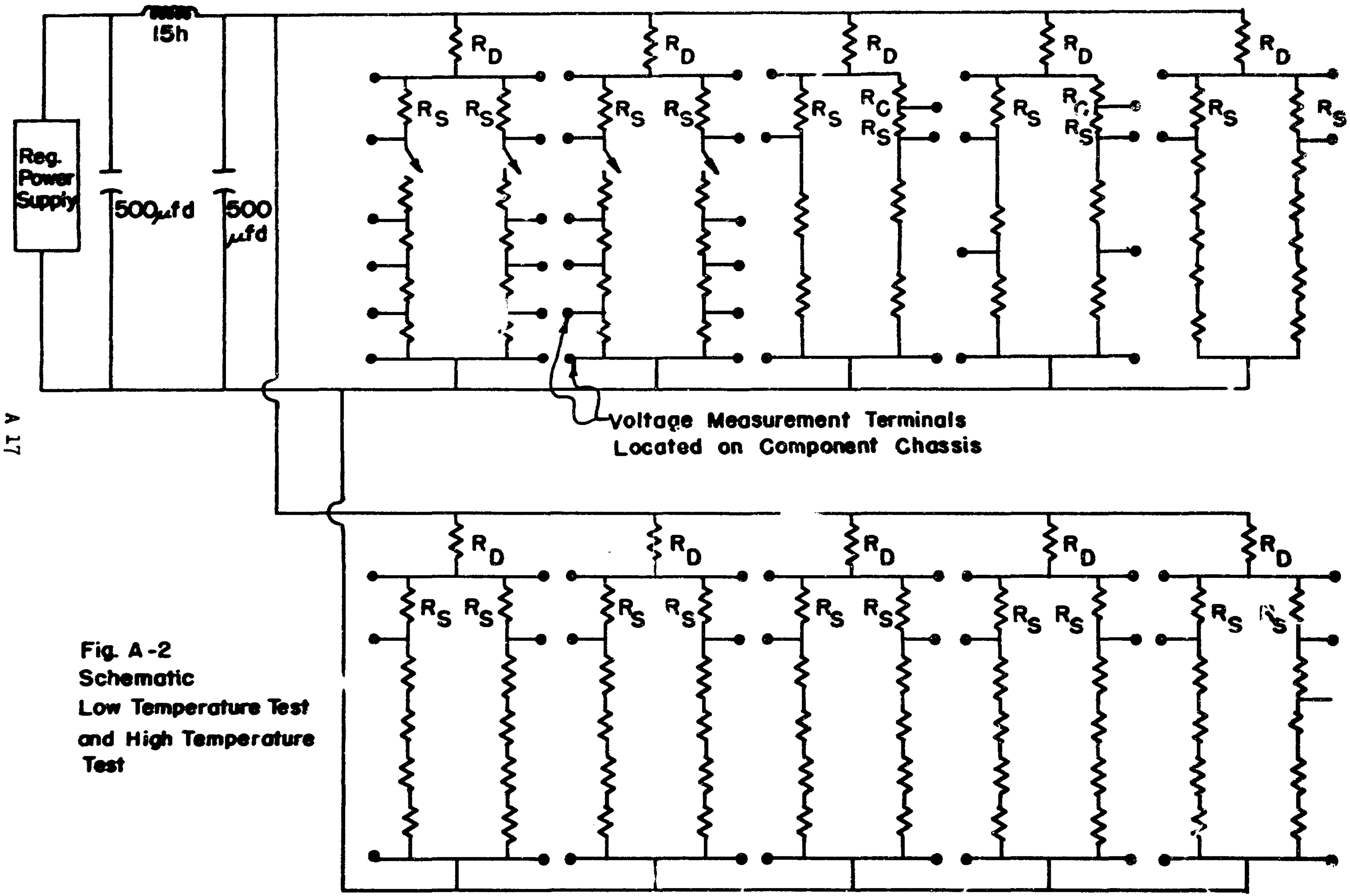


Fig. A-2
Schematic
Low Temperature Test
and High Temperature
Test

TEST APPARATUS

A. Low temperature test 125°C, 0-850 hours

1. Component Chasis-
   a.) Contains all circuit components other than thin film test components.
   b.) Contains all terminals used in voltage measurements
   c.) All circuit components values known to within ± 1.0%
2. Environmental control
   a.) Blue M "Stabil-Therm" gravity oven Model) V-12A, serial number KA-A3484
   b.) Maximum temperature deviation after thermal stabilization of ± 4.0°C
3. Other equipment
   a.) Power Supply - Hewlett-Packard model 712A, Purdue University number 566085
   b.) B+ monitor - Western D.C. voltmeter, model 430 serial number 28121, 1000 ohms/volt

B. Low Temp. test 850-1500 hours

1. Component chassis-same as low temp test 0-850 hrs.
2. Enviromental Control
   a.) Purdue Materials laboratory temperautre oven
   b.) Maximum deviation noted was ± 4°C
3. Other equipment
   a.) Power supply - Purdue Electronics laboratory Powers supply E 212, P.I. 55409
   b.) B+ monitor-none

C. High Temperature test 175°C

1. Component chassis
   a.) Contains all circuit components other than thin film test components
   b.) Contains all terminals used in voltage measurements
   c.) All component values known to within I 1.0%
2. Environmental control
   a.) Blue M "Stabil-Therm" gravity oven, model) V-12A, serial number KA 3617
   b.) Maximum temperature deviation noted was ± 4.0°C
3. Other equipment
   a.) Power supply-Hewlett-Packard, model 712A O. U. # 5660[illegible]
   b.) B+ monitor-Western D.C. voltmeter model 430 ser # 28121 at 1000 ohms per volt

D. Metering and Measurements devices - all tests

1. Boonton-Sensitive D.C. meters - model 95A Serial numbers 570 and 406
2. Leeds and Northrup resistance bridges, model 5430-A
   a.) L and N serial number 742641
   b.) P.U. # 567138

RESISTOR TERMINATION CATEGORY AND TEST SCHEDULE

Process Sequence	Test Temp. (°C)	Terminations of Resistors Nos. Are Coated	Terminations of Resistors Nos. Are Not Coated	Connection Treatment C-1	C-2	C-3	C-4
A	125	1-4	5-8	1-3-4	1-3-2	1-3-3	1-3-1
				1-3-6	1-3-5	1-3-7	1-3-8
	125	5-8	1-4	1-5-1	1-5-3	1-5-2	1-5-4
				1-5-6	1-5-5	1-5-7	1-5-8
	175	1-4	5-8	1-7-3	1-7-2	1-7-4	1-7-1
				1-7-6	1-7-7	1-7-5	1-7-8
	175	5-8	1-4	1-1-1	1-1-3	1-1-4	1-1-2
				1-1-5	1-1-8	1-1-6	1-1-7
	125	1-4	5-8	2-2-3	2-2-1	2-2-2	2-2-4
				2-2-7	2-2-5	2-2-6	2-2-8
	125	5-8	1-4	2-8-3	2-8-4	2-8-1	2-8-2
				2-8-5	2-8-6	2-8-7	2-8-8
	175	1-4	5-8	2-6-3	2-6-1	2-6-2	2-6-4
				2-6-7	2-6-5	2-6-8	2-6-6
A	175	5-8	1-4	2-4-2	2-4-3	2-4-1	2-4-4
				2-4-7	2-4-6	2-4-5	2-4-8
B	125	1-4	5-8	3-4-3	3-4-4	3-4-1	3-4-2
				3-4-7	3-4-6	3-4-5	3-4-8
	125	5-8	1-4	3-5-2	3-5-3	3-5-1	3-5-4
				3-5-6	3-5-5	3-5-8	3-5-7
	175	1-4	5-8	3-7-2	3-7-3	3-7-1	3-7-4
				3-7-8	3-7-5	3-7-7	3-7-6
	175	5-8	1-4	3-8-3	3-8-4	3-8-2	3-8-1
				3-8-7	3-8-9	3-8-5	3-8-6
	125	1-4	5-8	4-5-2	4-5-3	4-5-1	4-5-4
				4-5-6	4-5-5	4-5-8	4-5-7
	125	5-8	1-4	4-7-2	4-7-3	4-7-1	4-7-4
				4-7-8	4-7-5	4-7-7	4-7-6
	175	1-4	5-8	4-4-2	4-4-1	4-4-3	4-4-4
				4-4-7	4-4-6	4-4-5	4-4-8
B	175	5-8	1-4	4-3-4	4-3-1	4-3-3	4-3-2
				4-3-8	4-3-5	4-3-7	4-3-6
A_1	125		1-8			6-5-3	6-5-1
						6-5-5	6-5-7
	125		1-8			6-1-3	6-1-4
						6-1-8	6-1-5
	175		1-8			6-2-4	6-2-3
						6-2-8	6-2-5
A_1	175		1-8			6-6-[illegible]	6-6-3
						6-6-7	6-6-6

DETERMINATION OF CURRENT AND VOLTAGE FOR RATED POWER DISSIPATION

Microscopic measurements of sample components indicated that an assumption of each resistor having its eact design value in surface area was reasonable. Each resistor was then assumed to dissipate 25 watts per square inch of surface area. Since every panel consisted of two branches in parallel with each branch consisting of 4 resistors in series, the average current through any branch was determined as follows:

$$P_{Total} \;/\; Branch = P_{R_1} + P_{R_2} + P_{R_3} + P_{R_4}$$

$$P_{Total} \;/\; Branch = \langle I \rangle_{14}^2 R_1 + \langle I \rangle_{14}^2 R_2 + \langle I \rangle_{14}^2 R_3 + \langle I \rangle_{14}^2 R_4$$

$$\sum P_{R_1} = \langle I \rangle_{14}^2 \sum_{i=1}^{4} R_i$$

$$\langle I \rangle = \left(\frac{\sum P_{R_i}}{\sum R_i} \right)^{\frac{1}{2}}$$

The voltage across $R_{514} + R_{14}$ or $R_{558} + R_{58}$ was determined as $\langle E \rangle_{14} = \langle I \rangle_{14} [\Sigma R_i + R_5]$

$$\langle E \rangle = \frac{\langle E \rangle_{14} + \langle E \rangle_{58}}{2}$$

The dropping resistor was calculated as

$$R_D = \frac{(B+) - \langle E \rangle}{\langle E \rangle / R_p} \quad \text{where } R_p = R_{514} + R_{14} \;//\; R_{558} + R_{58}$$

The Power supply load is given by $R_L = \dfrac{1}{\sum \dfrac{1}{R_o + R_p}}$

Prior to initiation of the high temperature test, R_L was calculated as 850.9Ω and bridge measurements gave a value of 852.7Ω.

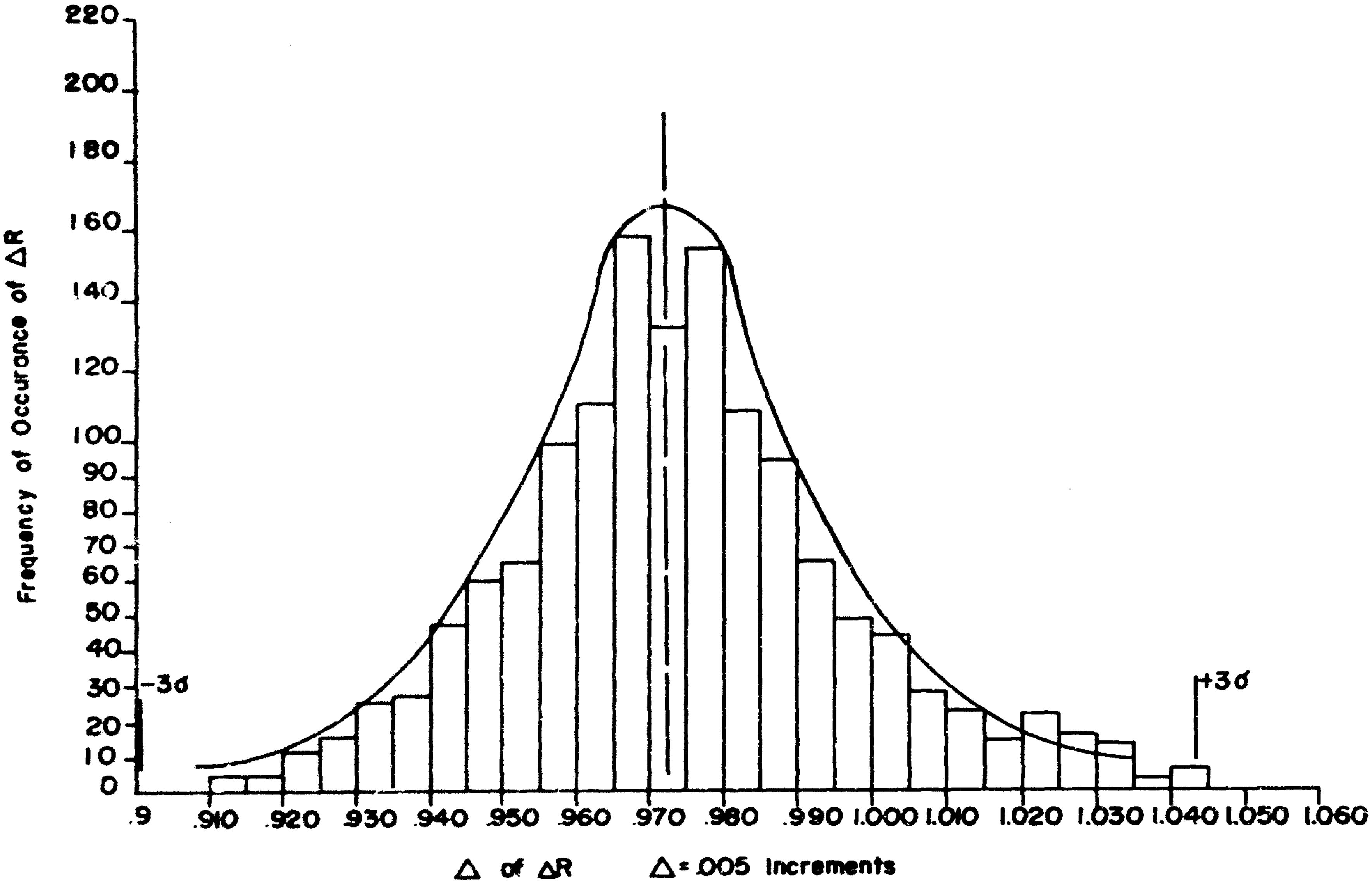


Fig. A-3 Distribution of Values of ΔR - All Catagories

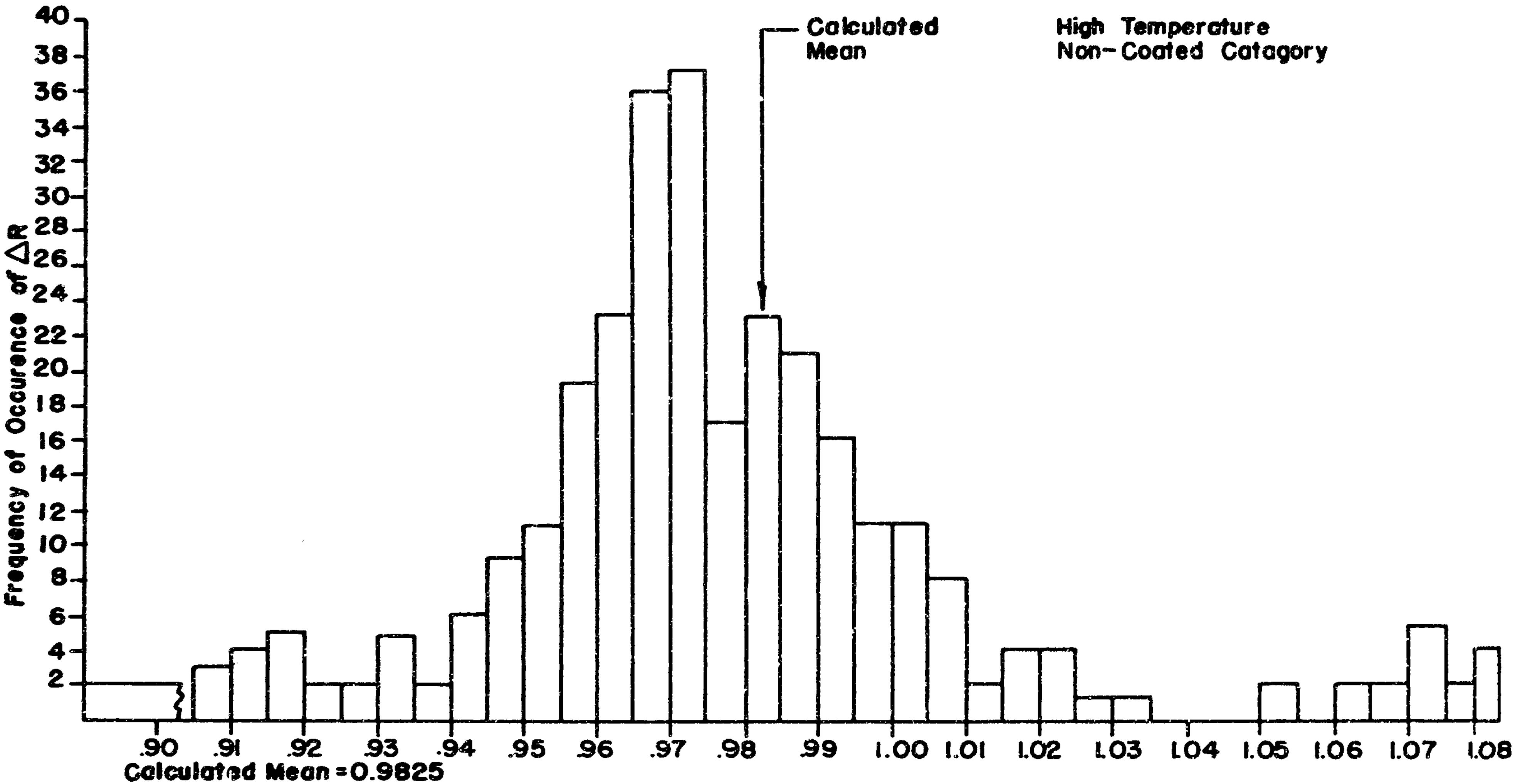


Fig. A-4 Distribution of Values of ΔR-- Non-Coated Catagory at 175° C

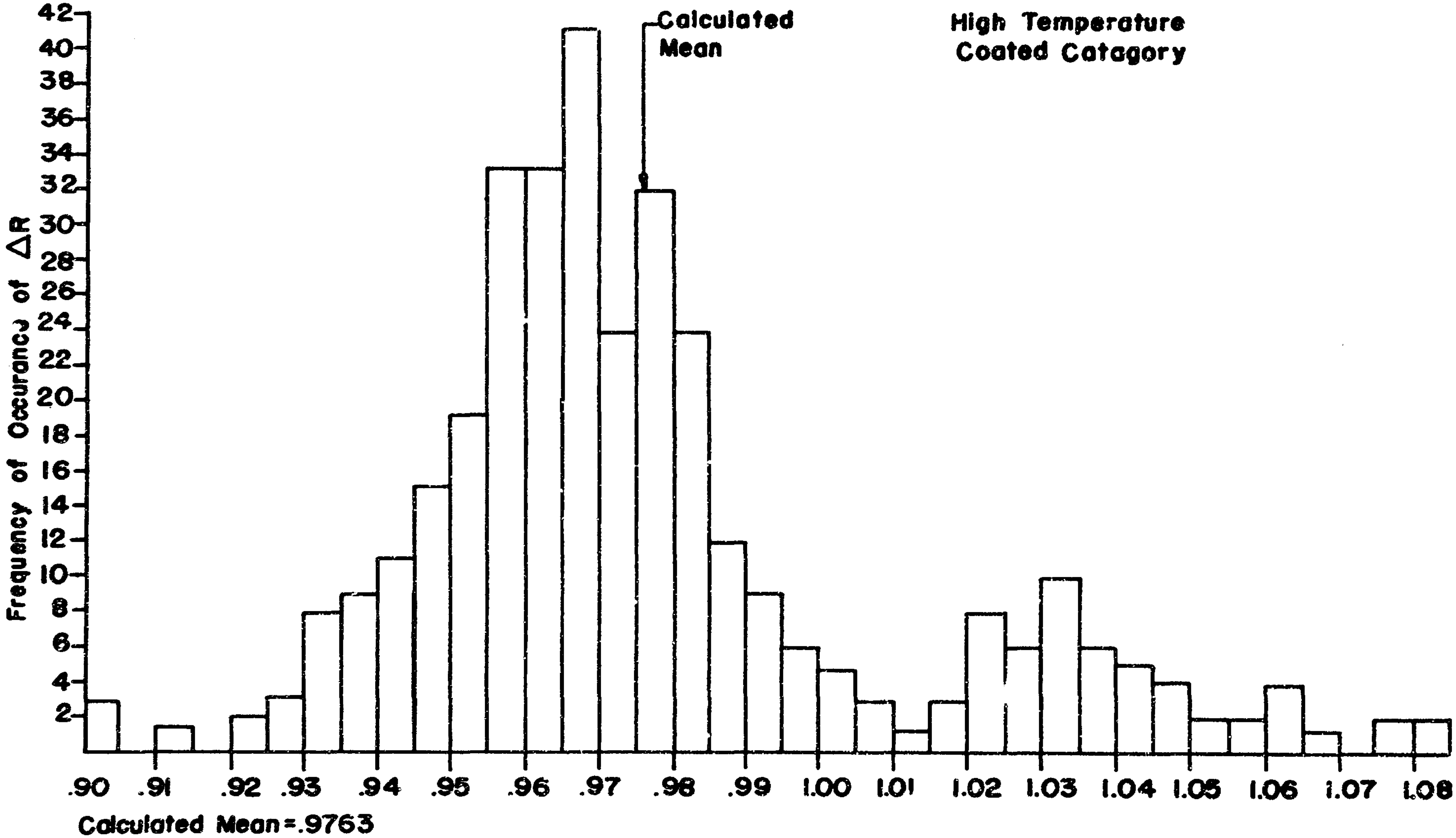


Fig. A-5 Distribution of Values of ΔR– Coated Catagory at 175° C

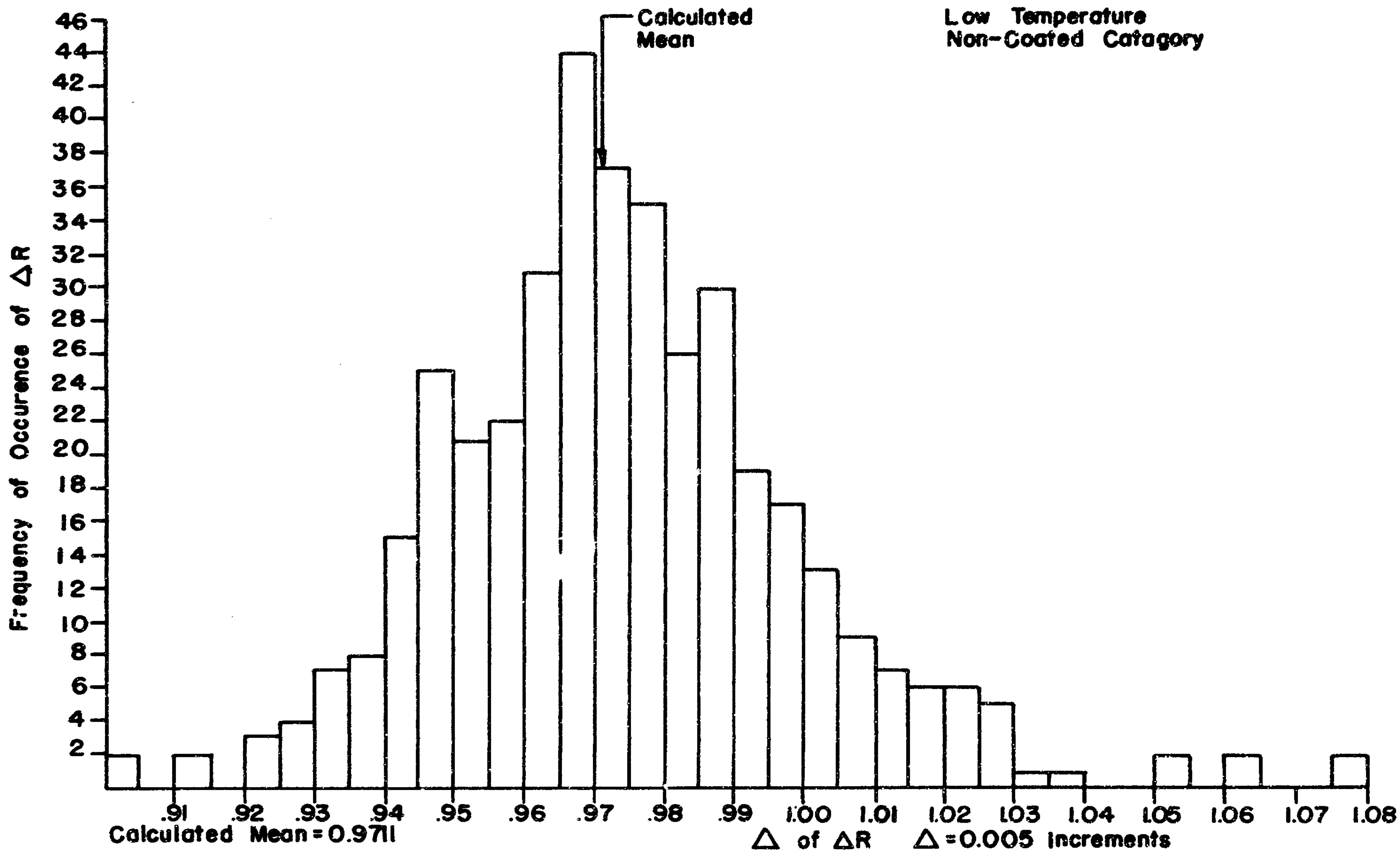


Fig. A-6 Distribution of Values of ΔR– Non-Coated Catagory at 125° C

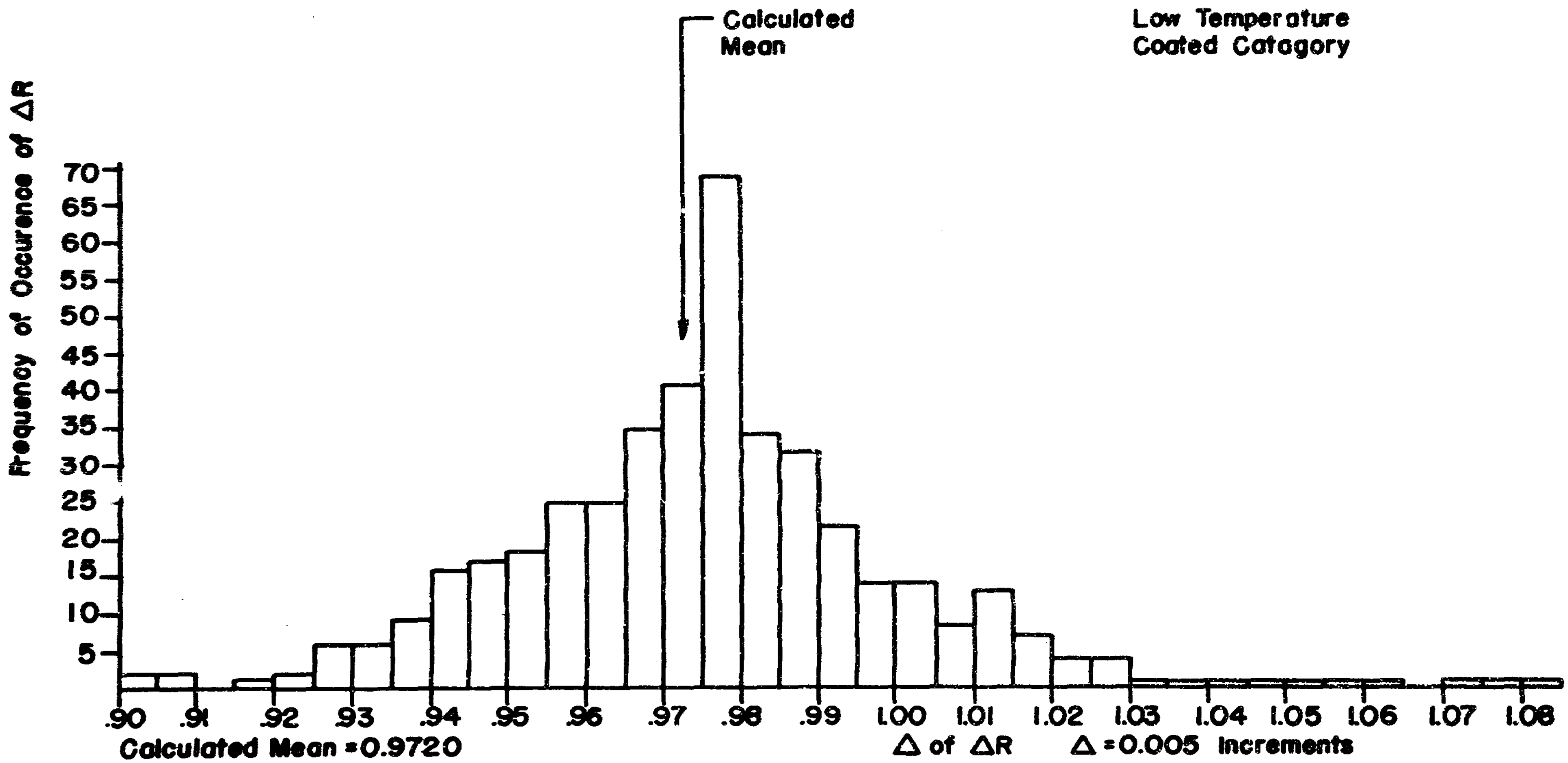
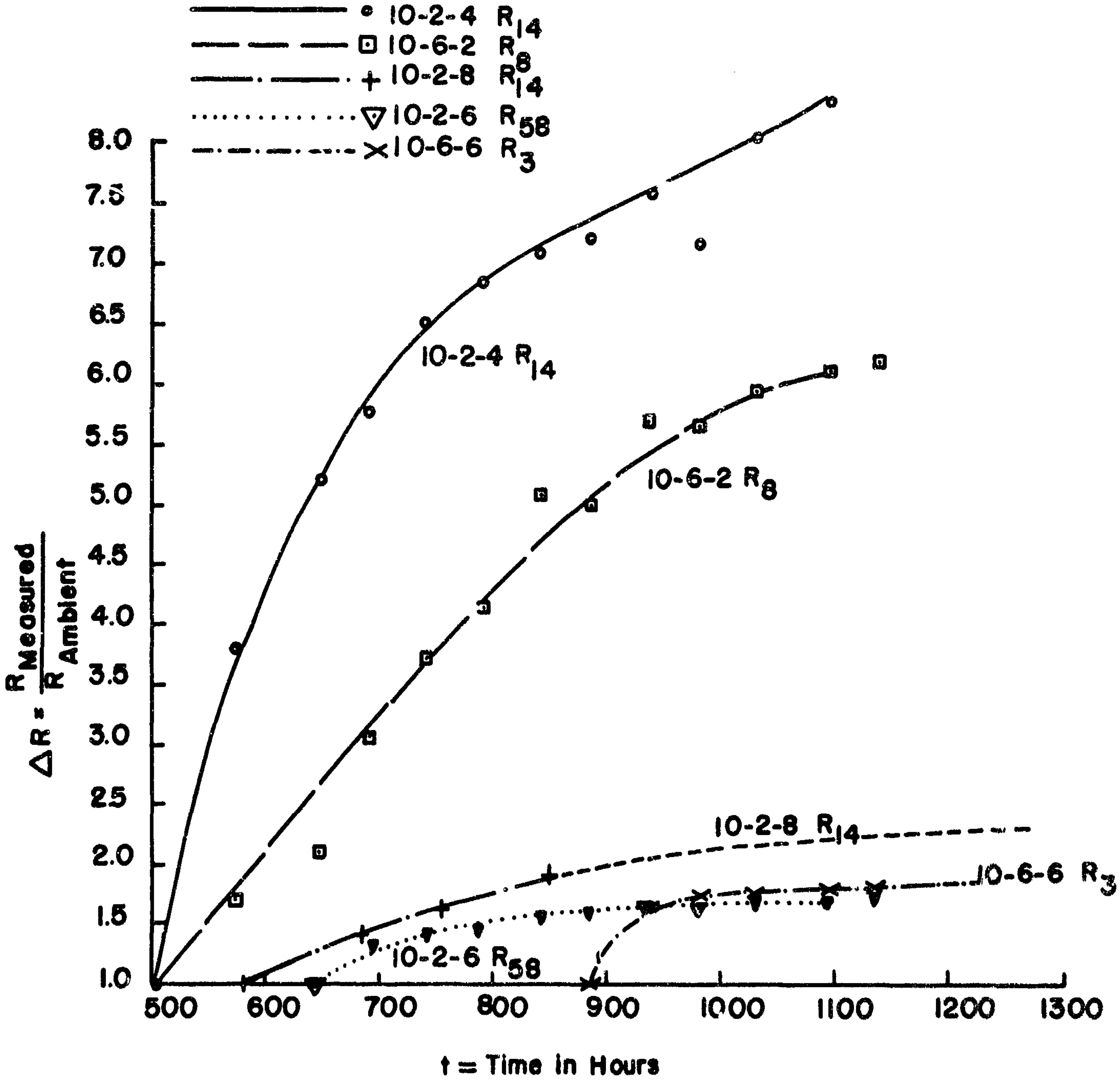


Fig. A-7 Distribution of Values of ΔR– Coated Catagory at 125°C



$\frac{R_{Measured}}{R_{Ambient}}$ Fig. A-8 Failure Curve ΔR vs Time

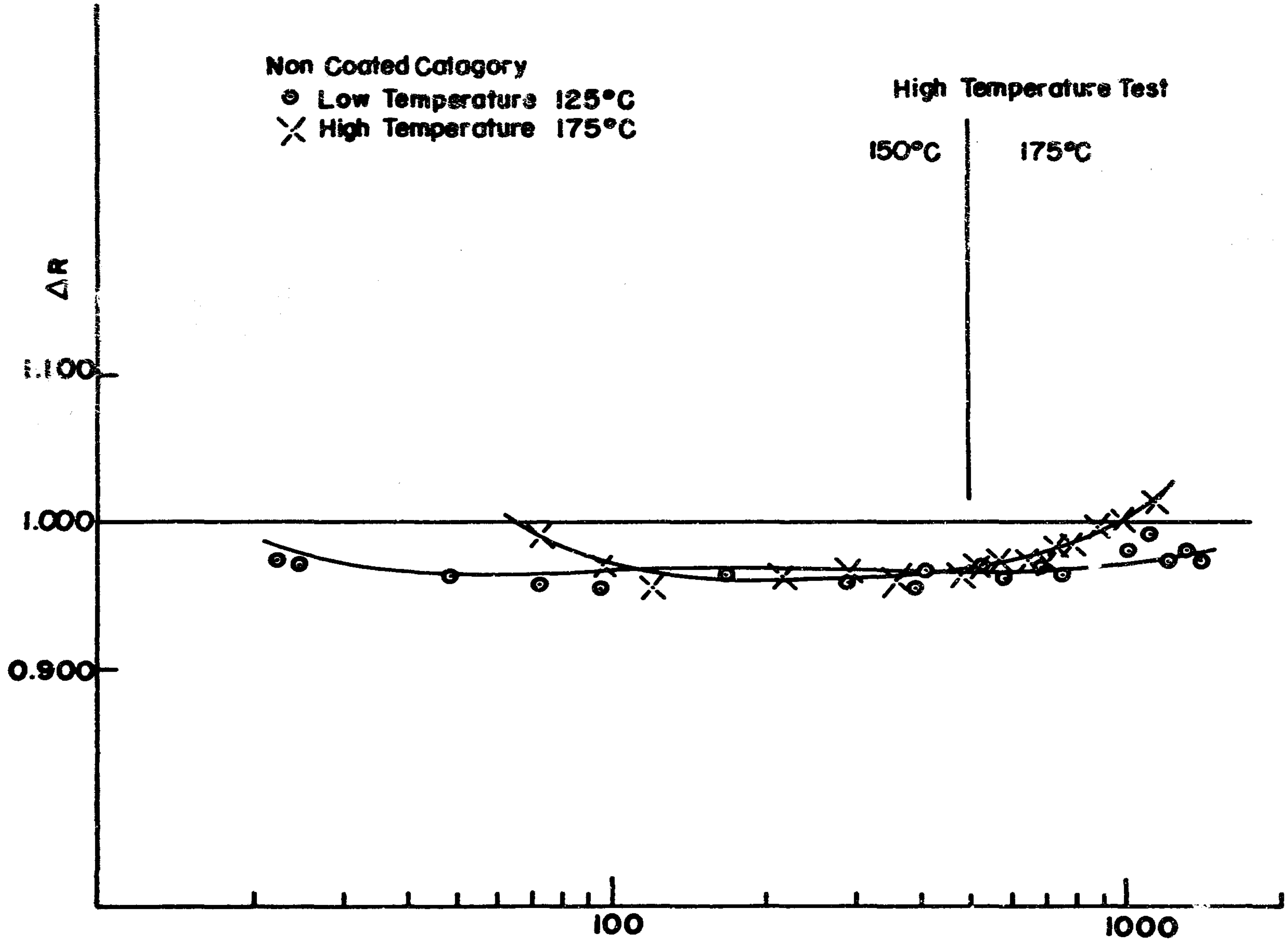


Fig. A-9 Failure Curve Average ΔR vs Time

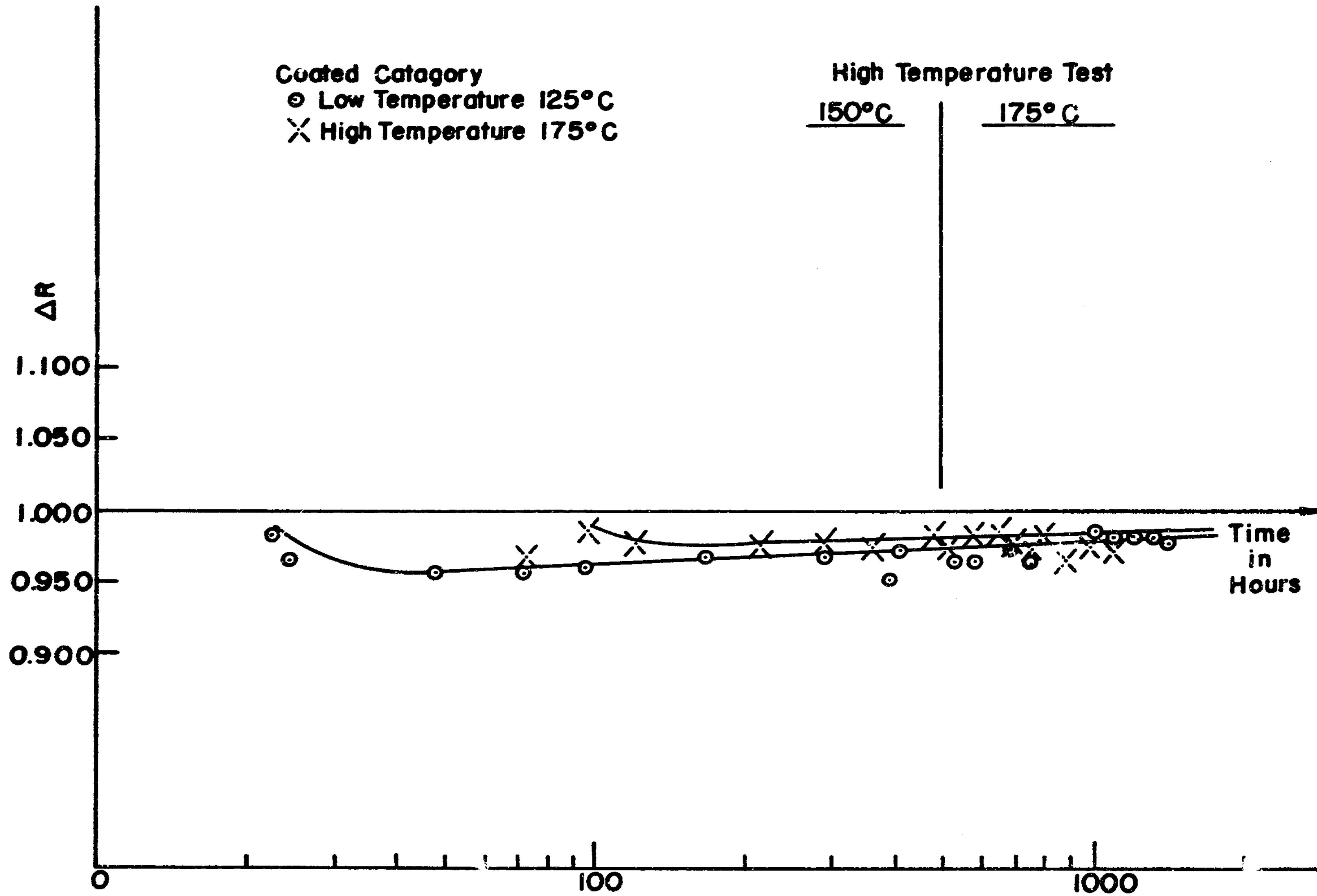


Fig. -10 Failure Curve Average ΔR vs Time

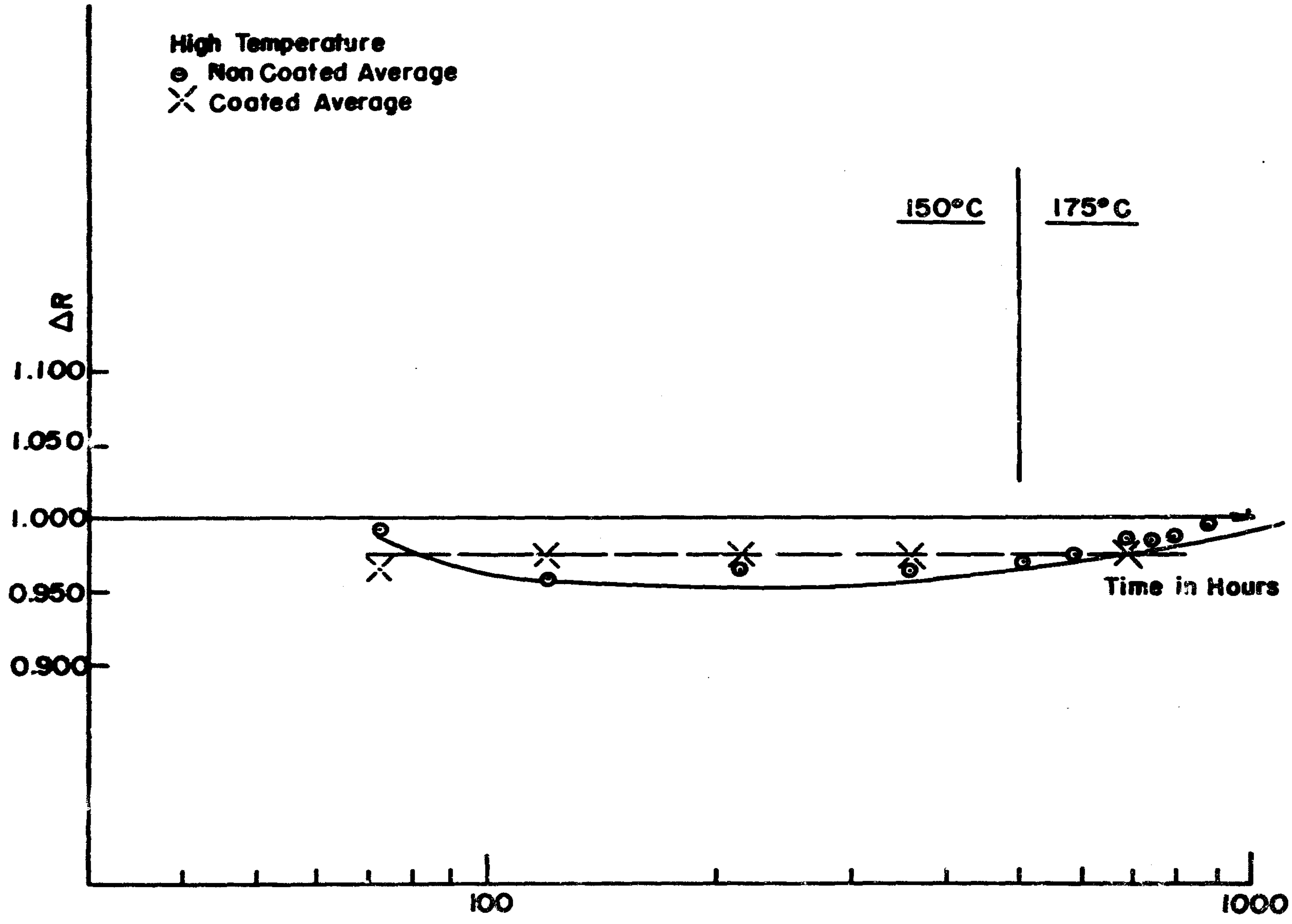


Fig. A-11 Failure Curve Average ΔR vs Time

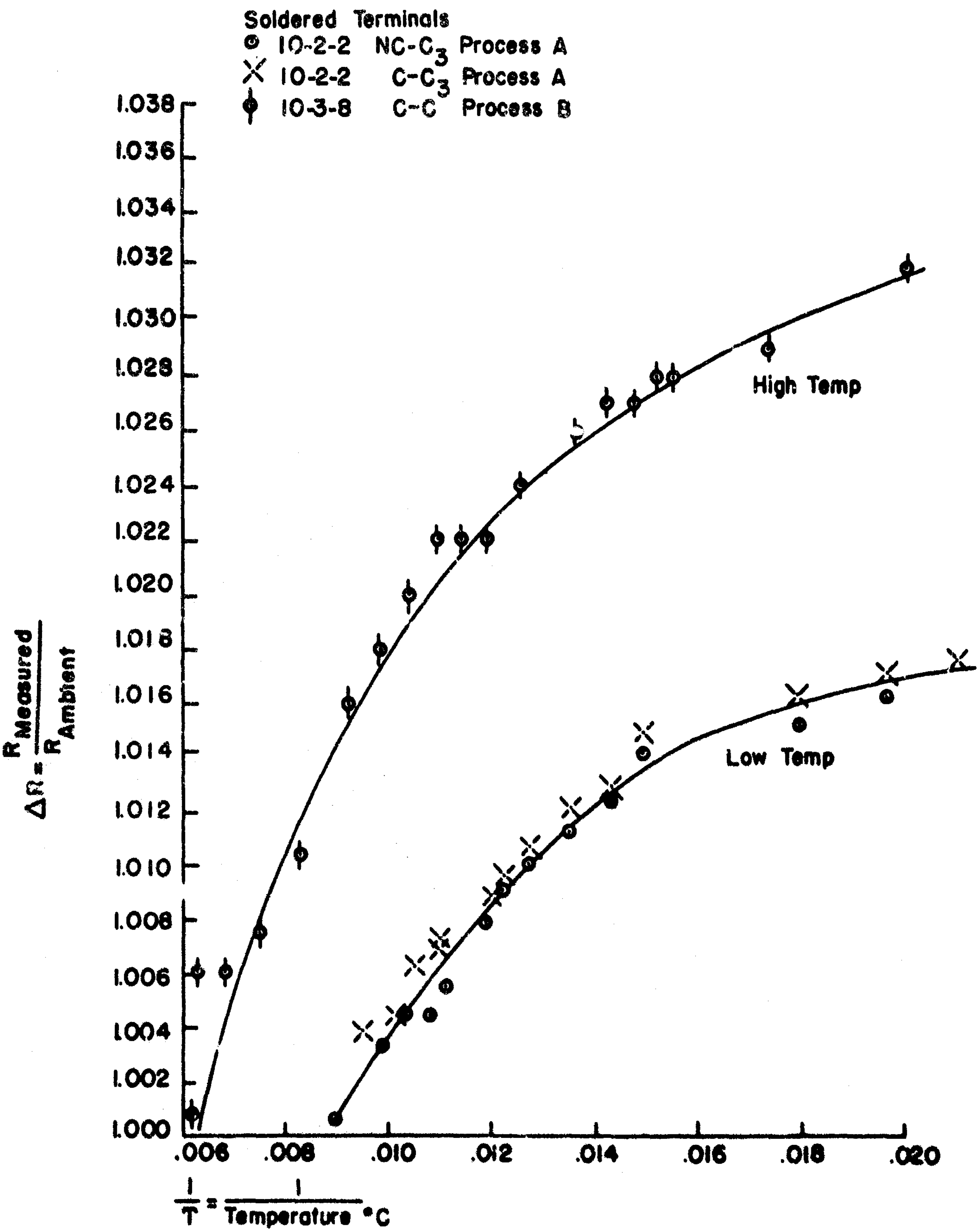


Fig. A-12 Cooling Curve ΔR vs $\frac{1}{T}$

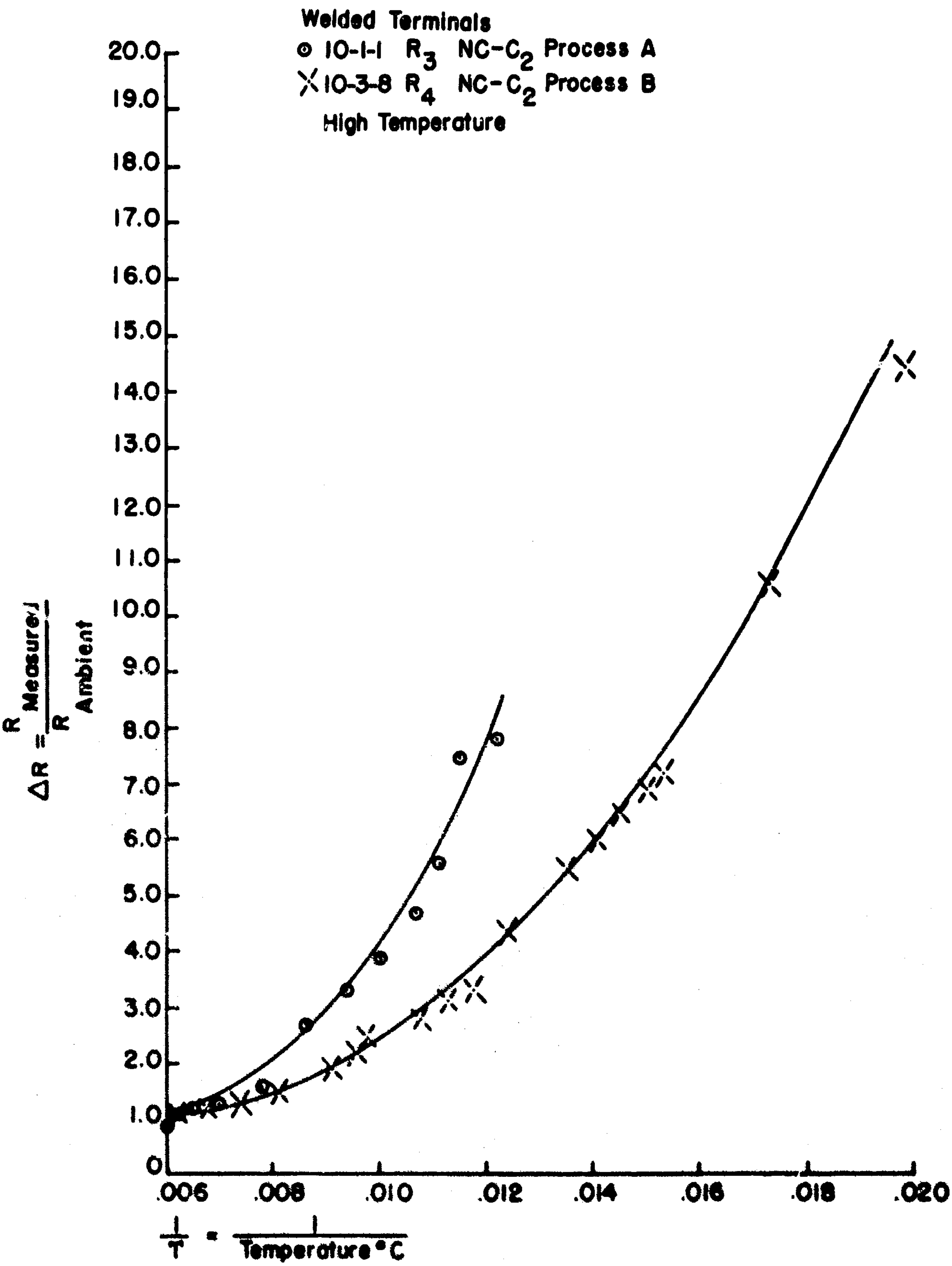


Fig.A-13 Cooling Curve ΔR vs $\frac{1}{T}$

Plate III

Surfaces of Terminations

(a) Impurities which adhere to the exposed copper apparently act as nucleation sites for oxidation.

(b) This peeling is typical of the uncoated terminals which were maintained at 175°.

(c) The uniform, granular surface structure is typical of the terminals which were maintained at 125°C.

(d) The post test discolorations found on gold terminals analogous to the color "flow lines" observed when heating a steel plate, were the only distinct marks not present before testing.

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